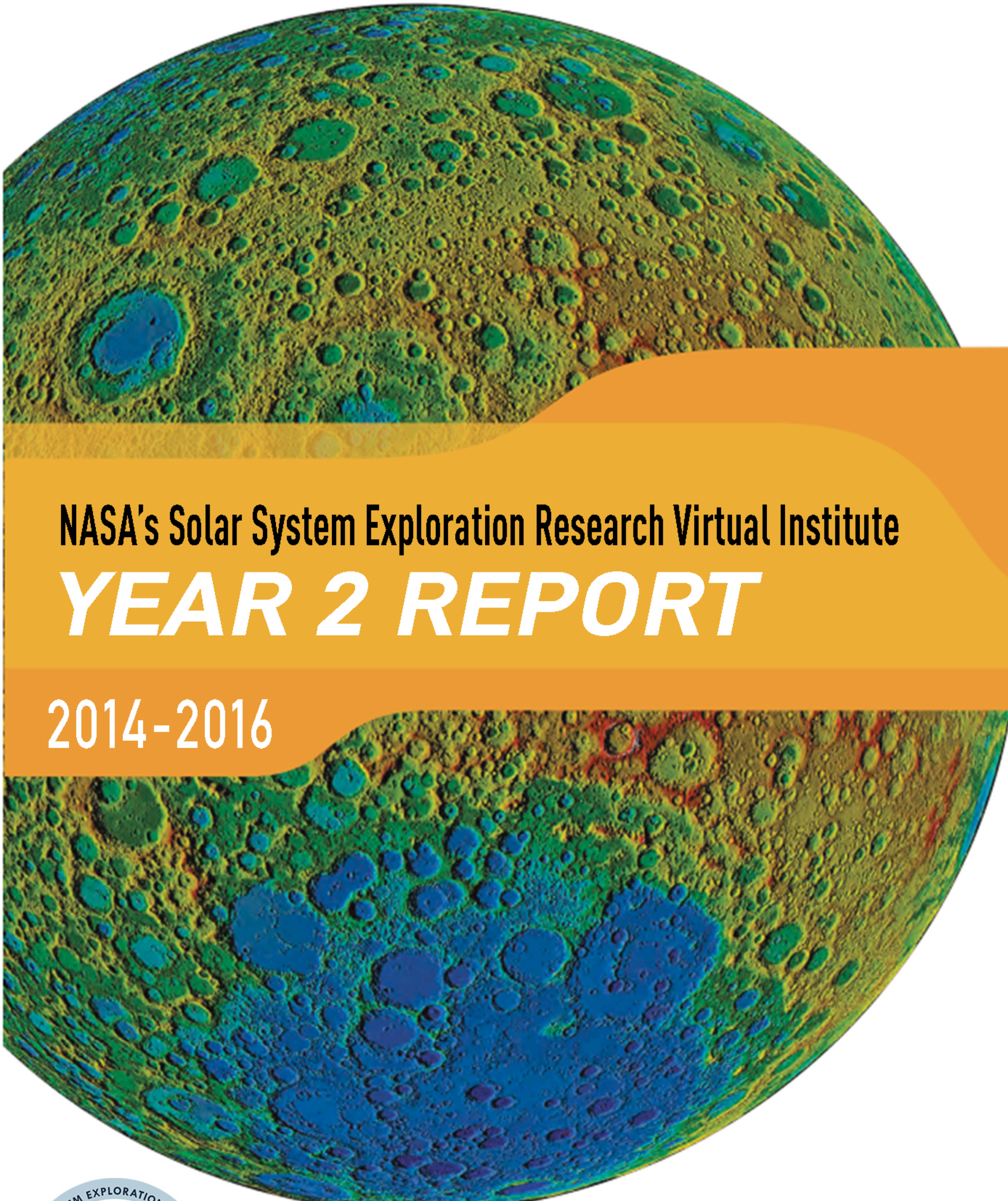
National Aeronautics and Space Administration

NASA's Solar System Exploration Research Virtual Institute

YEAR 2 REPORT

2014-2016



SOLAR SYSTEM EXPLORATION RESEARCH

SSERVI

VIRTUAL INSTITUTE

SSERVI Year 2 Progress Report
Institute for the Science of Exploration Targets (ISET)
PI William Bottke

1) Highlights of Research Activities from Year 2

Formation of Terrestrial Planets and Asteroid Belt. Using a new process in planetary formation modeling, where planets grow from tiny bodies called "pebbles", ISET researchers have published the first models that can form the entire Solar System by a single, unified process (Levison, Kretke, Walsh & Bottke, PNAS 2015) (Fig. 1). Where previous models begin with km-sized planetesimals and simulate their collisions and growth, a new mode of planetary growth known as Viscously Stirred Pebble Accretion (VSPA) has been developed to explain how the giant planets in our Solar System formed (Levison, Kretke & Duncan, Nature 2015).

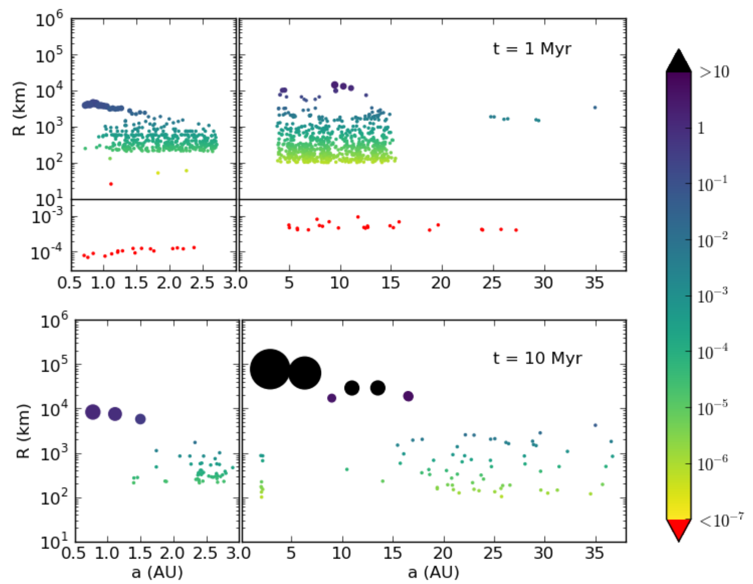


Figure 1. Two snapshots of a Solar System formed by pebble accretion. The top panels show our initial conditions, while the bottom panel shows our final results. *This is the first model to reproduce the structure of the solar system —Earth and Venus, a small Mars, a low-mass asteroid belt, two gas giants, two ice giants (Uranus and Neptune), and a pristine Kuiper Belt.*

With VSPA, dust readily grows to "pebbles" — objects a few inches in diameter—some of which gravitationally collapse to form asteroid-sized objects. Under the right conditions, these primordial asteroids can efficiently feed on the remaining pebbles, as aerodynamic drag pulls pebbles into orbit, where they spiral down and fuse with the growing planetary body. This allows certain asteroids to become planet-sized over relatively short time. The main factor(s) determining whether a primordial planetesimal grows to planet-sizes is its initial size and location. For reasonable initial distributions of sizes they would not have been able to grow effectively near the current location of Mars, or beyond, which provides a natural explanation for why it is so small – it was at the edge of where growth was efficient and there were no large embryos growing beyond it.

Additionally, this model has enormous implications for the history of the asteroid belt, as even fewer pebbles accrete on objects in the asteroid belt, keeping its net mass small as well. Previous models have predicted that the belt originally contained several Earth-masses' worth of material, meaning that planets began to grow there. The new model predicts that the asteroid belt never contained much mass in bodies like the currently observed asteroid. As this work dovetails with previous work to explain the formation of the giant planet cores through the accretion of pebbles, it creates the first comprehensive model of the formation of the Solar System in which the cores of the giant planets, the ice giants, the terrestrial planets and the asteroid and Kuiper belts were all formed from the accretion of pebbles. It also suggest the asteroid belt contains captured material the originally formed in the Jupiter-Saturn zone.

The ISET team has also been deploying their novel accretion and fragmentation code LIPAD to study some fundamental aspects of the "classical" stages of growth and how the dissipation of the solar nebula relates to the timing and nature of the onset of the final, giant impact, stage of growth that would be found in either "classical" or "pebble" models. To this end, a manuscript "Terrestrial Planet Formation from an Annulus" by Levison & Walsh is in its final stages of preparation.

Origin of the Moon. We are modeling the formation of the Moon from a giant impact (GI). In the GI theory, the Moon coalesces from debris ejected into an Earth-orbiting disk by the collision of a large planet with the early Earth. Understanding the nature of the impact, as well as the coupled dynamical and chemical evolution of the disk, is critical to assessing whether the GI theory yields a Moon consistent with what is seen. Work in year two primarily focused on modeling the Moon's initial volatile inventory, and the effects of the evection resonance on the Earth-Moon system.

*Lunar volatile depletion due to incomplete accreti*on (Canup et al. 2015, *Nature Geoscience*). The Earth/Moon mantles have similar compositions. The Moon, however, is more depleted in elements that vaporize readily (e.g., potassium); the reasons for this are unknown. It had been suggested that volatiles were evaporatively lost from the disk, but thermal escape appears minimal for expected disk conditions.

Dynamical models of the Moon's assembly suggest that the Moon initially accreted from the outermost disk, but later acquired up to 60% of its mass from melt originating from the inner disk. In this work we combined dynamical, thermal and chemical models to show that volatile depletion in the Moon can be explained by preferential accretion of volatile-rich melt in the inner disk to the Earth rather than to the growing Moon. Melt in the inner disk is initially hot and volatile-poor, but later as the disk cools volatiles condense. In our simulations, the delivery of inner disk melt to the Moon effectively ceases when gravitational interactions cause the Moon's orbit to expand away from the disk, and this termination of lunar accretion occurs prior to condensation of potassium and more volatile elements. Thus, the outer portions of the Moon derived mainly from the inner disk are expected to be volatile depleted, while more interior portions derived from the outer disk may be more volatile-rich.

Angular momentum loss due to the evection resonance (Ward & Canup 2016, in preparation). We are analyzing the effects of the evection resonance – in which the Moon's orbital precession period equals 1 year –on the Earth-Moon system angular momentum, which affects the types of impacts that could have produced the Moon. Capture of the Moon in evection results in growth of the Moon's orbital eccentricity as the Moon's orbit expands due to Earth tides. Eventually the eccentricity becomes high enough that lunar tides cause the Moon's orbit to contract. We find that the amount of angular momentum removed from the system depends on how long the Moon maintains a "quasi-resonant state" as its orbit is contracting, and that the final angular momentum depends on both the absolute rate of tidal dissipation in the Earth and the relative rate of tidal dissipation in the Moon compared to the Earth.

Solar System Bombardment. The asteroid belt is a key source of impactors hitting the terrestrial planets, the Moon, Phobos/Deimos, and other asteroids. The expected impact profiles for different models of the Solar System evolution can be obtained from numerical modeling. When compared to the actual historical record, as inferred from crater counts, Apollo data, Ar-Ar shock age constraints, etc., this work can be used to better constrain the early Solar System history. Here we performed self-consistent simulations of giant planet migration and inner solar system impacts over 4.5 Gyr. Highlights include: (i) Jupiter likely ejected a Neptune-sized giant planet during giant planet migration, (ii) encounters with this planet prior to ejection allowed comet-like planetesimals to be captured into many small body reservoirs; those in the asteroid belt explain the known P/D-type asteroids, and (iii) we have computed the likely contribution of comet impacts to the terrestrial planets and Moon (e.g., volatile delivery).

In addition, giant planet migration makes many lunar impactors from both an inner extension of the main belt (E-belt) at 1.7-2.1 AU and the main belt itself (2.1-3 AU). The gradual decline of E-belt impacts may produce Orientale/Imbrium-scale impacts on the Moon even 500 Myr after the dynamical instability. This raises a possibility that the dynamical instability triggering migration happened earlier that originally thought. Alternatively, studies of Mars's bombardment history indicate it experienced two bombardment phases (> 4.5 Ga; < 4.1 Ga) with doldrums between them. This scenario is consistent with lunar and meteorite constraints.

We have also modeled the environmental effects of large collisions on the Hadean Earth. The work proposes to resolve the "faint young Sun paradox", where Earth's early surface should have been frozen due to the reduced energy input from the infant Sun. Geochemical constraints from Hadean zircons, however, show that liquid water could have been present on the Earth's surface ~4.3-4.4 Ga. In our work, we show the earliest bombardment flux generated 10's of bars of greenhouse gases, including carbon dioxide, thus potentially mitigating the reduced solar input. Indeed, our simulations indicate this process alone could have resulted in protracted clement surface conditions for 10s to 100s Myr, depending on relevant parameters (see Fig. 2).

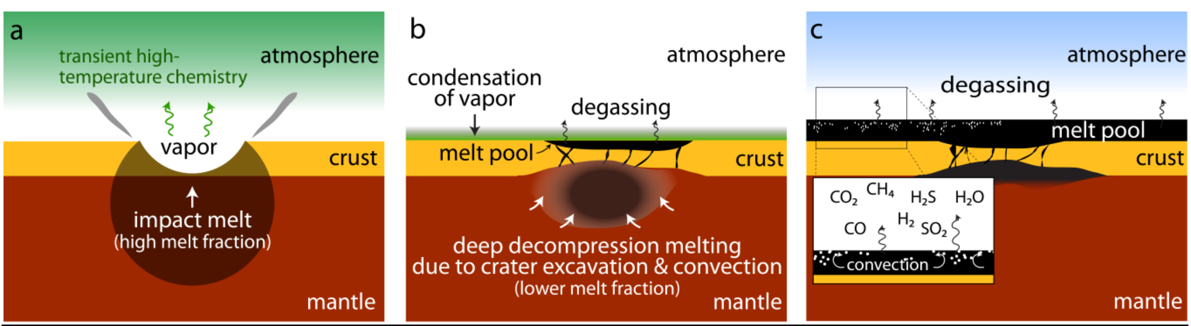


Figure 2. Schematic cross section through an impact-generated melt pool and subsequent outgassing. a: A large impact results in the formation of a transient, silicate-rich high temperature atmosphere, prior to impact-generated melt spreading. B: Upon fast cooling, the transient atmosphere condenses, while deep-seated, impact-generated melts spread on the surface. c: As impact-generated melts spread, they release greenhouse gases, as carbon dioxide, which are capable to produce clement surface conditions.

We also examined more recent impact records on the Moon, Venus, Earth, and Mars. For the Moon, we have used Diviner data in a unique way to estimate the ages of large lunar craters over the last 1 Gyr. We can show the inner solar system impact flux has tripled over the last 0.4 Ga. Similarly, we have computed ages of young lunar craters with *D* > 50 km using the density of small, superposed craters (< 1 km) measured on their floors. They suggest the impact flux has not been constant over the last 3 Ga for D > 1 km impactors, as has been previously assumed, but has potentially been "wavy" with spikes and lulls. Finally, we deduced a new crater scaling law using NEOs/young craters on Moon/Venus/Mars. Our results differ from hydrocode results, and they imply the surface age of Venus is ~150 Ma.

Properties and Populations of NEAs. We have focused on the mechanics of asteroids held together by weakly cohesive bonds that may exist in the regolith that mantles and exists throughout these bodies. This work has included the stress and failure analysis of observed active asteroids which have had catastrophic break-ups, the analysis of the fast-spinning asteroids such as 1950 DA which provides unique insight into the manner in which these asteroids fail, and has entailed working through detailed predictions of how cohesive asteroids may evolve geophysically as a function of strength and friction (Fig. 3). A new aspect of research over the past year has focused on the dynamics of surface motion on small bodies. This research has application to both exploration activities and to more detailed constraints on surface landslides on small bodies.

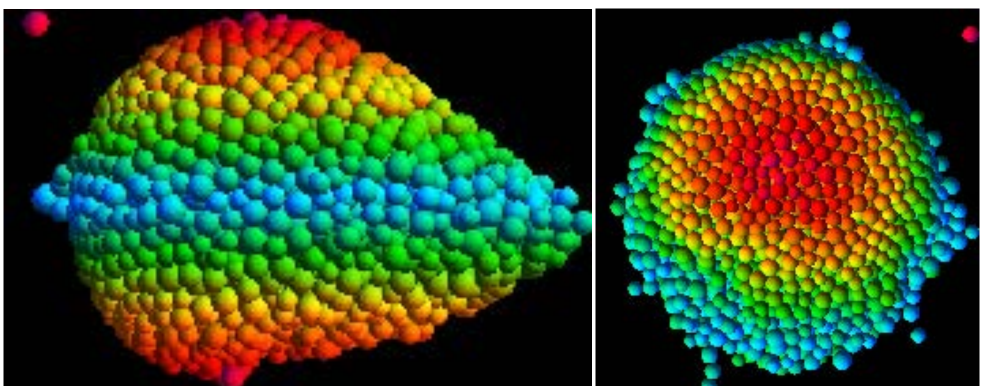


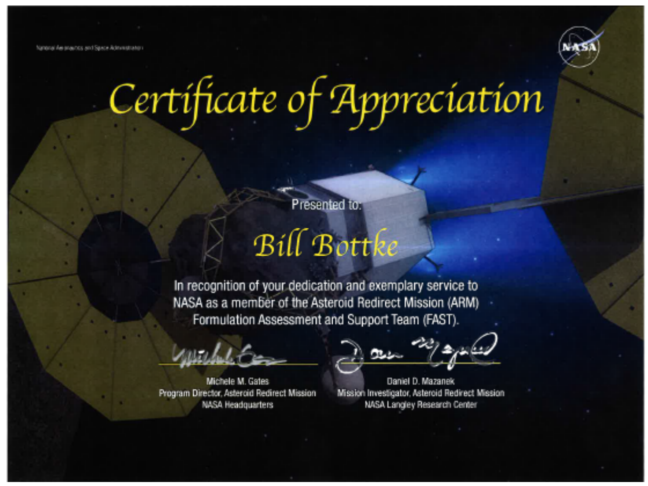
Figure 3: Side and top view of a cohesive rubble pile asteroid after failure and fission of a binary-sized component. The shape of the post-fission aggregate has morphological similarities to the primary of binary asteroid 1998 KW4 (Sanchez & Scheeres, Icarus 2016, in press).

We have also obtained a total of 5 nights of telescope time in the first half of 2016 on the 8 meter diameter Subaru telescope's Hyper Suprime-Cam (HSC) camera for a survey to detect meter-scale asteroids that are temporarily captured in the Earth-Moon system --- minimoons. The first two successive nights of the survey took place in early January 2016 under excellent sky conditions and the 1.5 TB of image data is currently being processed to identify asteroids. The processing pipeline was developed by a small team of collaborators at the University of Hawai`i by combining components of existing image analysis software and the Pan-STARRS Moving Object Processing System. This software should be will be capable of real-time operation for the subsequent survey nights, thereby enabling greater sky coverage with increased likelihood of discovering a minimoon. Bolin et al. (2014) optimistically calculated that a 5 night Subaru HSC survey has about an 80% likelihood of detecting a minimoon but we estimate that the discovery probability in our survey is about 40% with a more realistic survey scenario.

2) Inter-team collaborations

Members of our team have been interacting with David Kring's team (*CLSE)*, Carle Pieters' team (*SEEED*), Dan Britt's team (*CLASS*) on a wide range of topics related to the bombardment history of the Earth, Moon, asteroid belt, the origin of Phobos and Deimos, and the evolution/nature of near-Earth and main belt asteroids. We also have had scientific interactions with Mihaly Horanyi's team (IMPACT) and Andy Rivkin's team (VORTICES)

- Marchi et al. (2016; EPSL) discussed the bombardment of Hadean Earth and its effect on the earliest atmosphere with Lindy-Elkins Tanton of SEEED.
- Bottke et al. (2015; Science) discussed ejecta from the Moon-forming impact hitting main belt asteroids and making ancient impact ages in meteorites with Tim Swindle from CLSE.
- Bottke/Scheeres interacted with Dan Britt and Huberto Campins (CLASS) on the Formulation Assessment and Support Team (FAST). They studied many aspects of the Asteroid Redirect Mission (ARM).



- Bottke is an editor for the Asteroids IV book with supervising editor of the Space Science Series R. Binzel (SEEED).
- Robin Canup contributed to the SSERVI Phobos/Deimos graduate course run by Dan Britt (CLASS).
- Kevin Walsh worked with Rick Binzel (SEEED) on their Asteroids IV chapter; it discussed "The compositional structure of the asteroid belt".
- The U. Colorado team led by Co-I D. Scheeres has on-going collaborations with the CLASS team led by Britt and with the CU team led by Horanyi
- Scheeres worked with Dan Britt (SEEED) on their Asteroids IV chapter "Asteroid interiors and morphology".
- Bottke discussed the "Link between the potentially hazardous Asteroid (86039) 1999 NC43 and the Chelyabinsk meteoroid tenuous" with V. Reddy of CLASS (Icarus, 2015)
- Bottke, Marchi are involved with O. Abromov from CLSE on a project to study how impact heating and subsequent hydrothermal circulation may produce observable alteration signatures near or within craters.
- Bottke has been involved with on-going work related to the missing asteroid family for Ceres with A. Rivkin of VORTICES. The first verision of this work was published last year in Icarus.
- Bottke is on the Psyche Discovery mission (Phase A) led by Elkins-Tanton (SEEED). Several abstracts have come from this, and they will lead to some papers.
- Bottke and Dave Kring (CLSE) are sharing the SSERVI postdoc Katherine Kretke. Our goal is to test various planet formation scenarios using terrestrial, lunar, and meteorite samples.

3) EPO activities

Summer Science Program. Kirchoff, Kretke, and Salmon served as science lecturers for the Summer Science Program in New Mexico and Colorado in July 2015. This program offers SSERVI-rich participatory science experiences to 36 high-performing high-school students at each session in a continuing partnership with Summer Science Program, Inc. (SSPI).

ISET members guided the students through using the numerical integrator Swift to integrate the orbits of their observed asteroids into the future. The students then analyze and present their results on the fate of their asteroid to their peers. We also provide a scientific lecture to the students on asteroid populations and their dynamical evolutions, including chaos theory. Using feedback from the students, Kirchoff, Kretke, and Salmon collaborated with Levison, Dones, and Nesvorny to improve the written instructions for the students and the oral lectures.

Helping Librarians Bring Science to Their Patrons. On February 24-25, 2015, ISET sponsored a training for 30 librarians from across the United States on SSERVI content and activities, conducted by the Lunar and Planetary Institute (LPI). Kirchoff shared how the Moon's features and rocks record its "life story," and led select activities. Participants learned about the origins, composition, and scale of the Moon, asteroids, and meteorites. Participants were prepared to use hands-on activities and other NASA resources and were certified to borrow lunar and meteorite sample disks from NASA Johnson Space Center's Astromaterials Research and Exploration Science (ARES) program.

Evaluation results were extremely positive. When surveyed, all of the participants (100%) were "confident" to "very confident" in their ability to successfully implement the activities, and planned to implement activities. All (100%) also indicated that the training was effective, provided sufficient opportunities to interact, and prepared them to use the activities and resources and to share NASA science with their community. Qualitative evaluation survey data indicated strong interest regarding the science presentations.

In 2016, librarians and out-of-school educators will be invited to attend an ISET webinar featuring select hands-on lunar activities from the Explore! Marvel Moon module. New activities and resources will be posted to the Explore! Marvel Moon site, including revised activities and content and a meteorite activity evaluated in 2015.

Sharing Results. Six ISET scientists participated in the 2015 Denver Comic Con (including SSERVI-related science talks; Kirchoff and Kretke ran a planet building activity for preschool and elementary children). LPI contributed an article about the International Observe the Moon Night — including a librarian's participant's use of ISET resources — for the May/June edition of Legacy Magazine. Kirchoff was a science advisor for the Commack High School LPI ExMASS team (Fall 2015-Spring 2016).

4) Student/Early Career Participation

Research Scientist Kevin Walsh. Kevin Walsh has been working with the ISET team at SwRI on models of planet formation and asteroid physical properties and dynamics. During the past year Dr. Walsh has been promoted from Research Scientist to Senior Research Scientist at SwRI. He gave invited presentations of SSERVI work at the IAU, AGU and Gordon Research conference in 2015 and became a Kavli Fellow based on his invitation to present at the Kavli Frontiers of Science Indo-American Symposium at the National Academy of Sciences in August 2015.

Research Scientist Julien Salmon. Julien Salmon has been working with Robin Canup on models of lunar origin. During the past year he collaborated on a project to explain the lunar volatile depletion. He provided numerical results on the accretion of the Moon from the protolunar disk (Salmon and Canup 2012), that were then combined with thermal and chemical models to determine the amount of volatiles incorporated into the Moon during its accretion (Canup et al. 2015, Nature Geosc.). Salmon also gave a teacher's seminar in which he gave ~30 high-school teachers an overview of our current knowledge of how the Moon formed.

Research Scientist Katherine Kretke. Katherine Kretke has been working with Hal Levison, Kevin Walsh, Bill Bottke and Martin Duncan to implement pebble accretion and gas disk evolution in LIPAD and create models that have successfully reproduced the Solar System using these models. She also has worked with Hal Levison to and identified a possible way to look for evidence of pebbles preserved in comets. Additionally, she has been having discussions with David Kring (PI of CLSE) on identifying possible cosmochemical constraints that can be used to test the models she has been making. That relationship will grow over the next two years as she transitions from being an ISET post-doc to a SSERVI fellow.

Senior Research Scientist Paul Sanchez: Dr. Sanchez has been promoted to Senior Research Scientist from Research Associate since the start of the SSERVI grant. He has been supported for a majority of his time, performing research on the mechanics and physical evolution of rubble pile bodies subject to rapid spin rates. Sanchez also has started collaboration with members of the University of Colorado-based IMPACT SSERVI team.

Research Associate Masatoshi Hirabayashi: Dr. Hirabayashi was initially supported by the SSERVI grant to perform stress and failure analysis of asteroids using commercial and custom continuum mechanics models. He has subsequently taken a post-doc position with Dr. Jay Melosh at Purdue University.

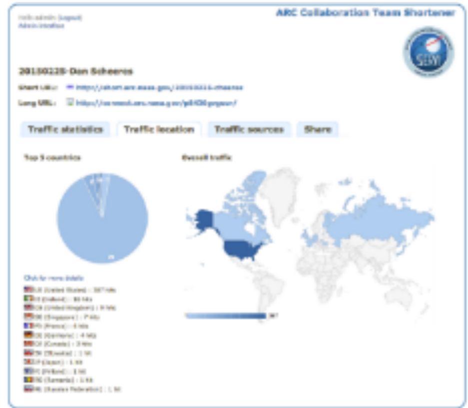
Graduate Student Travis Gabriel: Mr Gabriel performed research at CU under the SSERVI grant focused on the energetics of stable configurations of rubble pile asteroids. He achieved a Master's degree at CU and has now transitioned into the PhD program at Arizona State University where he is working with Dr. Erik Asphaug.

Graduate Student Stefaan Van wal: Mr. Van wal is currently supported as a PhD student by the SSERVI grant. His focus is on the dynamics of motion on the surfaces of small bodies, with applications to both exploration activities and to geophysical processes on small bodies.

Center for Lunar and Asteroid Surface Science (CLASS)
Annual Report for 2015

I. CLASS Team Projects:

CLASS Seminar: CLASS sponsors biweekly seminars that are broadcast over AdobeConnect featuring cutting-edge lunar and asteroid exploration science. These seminars have been very popular, particularly since they are recorded by SSERVI central and available broadly to remote collaborators. This calendar year CLASS hosted a total of 17 speakers who accumulated a total of 2,611 online viewers during the live streaming and of the recorded/archived talks, from 55 different countries. Countries included almost all European countries, Nigeria, South Africa, most of South America, India, Pakistan, Afghanistan, Japan, Australia, New Zealand, and South Korea. The most popular talks included Charles Radley (The Lunar Elevator) with 1157 views and Dan Scheeres (Cohesion in Rubble Pile Asteroids) with 465 views. Viewer statistics are attached at the end of this report.



CLASS Student Exchange: Provides travel funding for exchanges of students between CLASS investigators and to attend in-depth workshops lead by CLASS investigators. The objective was to broaden the research and intellectual scope of CLASS-sponsored students and to foster close collaboration between CLASS investigators. CLASS supported 3 exchanges that included:

- Charles Schambeau: Exchanged with Jürgen Blum (Institut für Geophysik und extraterrestrische Physik, TU Braunschweig) and Javier Licandro (IAC, Spain). His research is on development and implementation of a thermophysical/chemical model of the enigmatic comet 29P/Schwassmann-Wachmann 1 and this exchange allowed him to incorporate experimental results and new models of volatile sublimation from porous materials.
- Zoe Landsman: Exchanged with Javier Licandro (IAC, Spain). Her research focus is on the collisional evolution and space weathering of main asteroid belt families. This work included a mid-infrared study of the Veritas collisional asteroid family using the facilities at the IAC.
- Jenna Jones: Attended the TherMoPSII workshop to support her thermal modeling of S-complex asteroids. She uses radar-derived shape models to constrain thermal properties of the asteroids in order to derive the compositional and thermal heterogeneity of the asteroid surface material.

CLASS Sponsorship of Workshops: CLASS is proactive in creating dynamic intellectual environments that allow the maximum interchange of ideas and approaches across interdisciplinary lines. We provided modest funding to help sponsor several workshops that are typically led by our CLASS co-I's or collaborators. CLASS sponsored TherMoPS II (Thermal Models for Planetary Science II, http://www.iac.es/congreso/thermopsii/) in Tenerife, Spain June 3-5, 2015 hosted by the Institute of Astrophysics of the Canaries (IAC). CLASS also hosted the "Workshop on Asteroid Simulants" jointly with Deep Space Industries at the Florida Space Institute, October 6-7, 2015.

CLASS Visiting Scientists: CLASS sponsored a series of visiting Scientists at UCF to foster a deeper collaboration and exchange between CLASS team members. These included Thom Orlando (Georgia Tech), Larry Taylor (U Tenn), and Cyril Opiel (Boston College). Typically a visiting scientists gives a CLASS seminar, leads a local discussion group with graduate students, and consults with CLASS faculty at UCF.

A bolide over Canada captured by Co-I Peter Brown's optical network

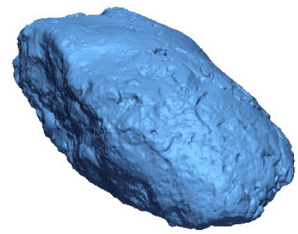
CLASS Directed Brainstorming: CLASS takes advantage of the AdobeConnect capabilities provided by SSERVI by assembling CLASS team members to support addressing critical exploration science questions for our NASA partners. We ran two directed brainstorming sessions for the NASA-JSC Swamp Works group to address science questions related to the proposed Asteroid Redirect mission.

CLASS Support for HEOMD Activities: CLASS is proactive in providing science support when requested for NASA HEOMD exploration needs.

- During 2015 we continued to support a SBAG special action group that addressed HEOMD questions on the strength, cohesion, chemistry, structure, and surface properties of small asteroids.
- CLASS provided ARM, JSC, and JPL groups with asteroid simulants to support their work on regolith properties and boulder capture.
- CLASS worked with JSC to develop the Strata-1 microgravity regolith experiment that will be launch to ISS March 10, 2016
- CLASS supported experiments in asteroid ISRU by JPL and plume interactions on asteroids.
- CLASS team members Britt, Campins, Abell, and Scheeres were named to the ARM FAST and supported its report development. Co-I's Durda, Dove, Metzger, and Opiel provided input and data for the FAST report. Opiel measured meteorite thermal properties to support the report.

CLASS is also conducted a range of research programs that will support HEOMD exploration priorities. These are listed below under the individual CLASS scientists.

CLASS New Tenure-Track Faculty: As part of UCF's commitment to SSERVI and CLASS, Dr. Adrienne Dove was hired as an Assistant Professor of Physics at UCF in August 2015. A search is underway for a second tenure-track position that was created as a direct result of CLASS.



Laser shape model scan of lunar meteorite NWA 10404 obtained as part of Macke and Britt density study of new lunar meteorites.

CLASS Advanced Planetary Science Education: CLASS and SEEED (and SSERVI) jointly sponsored an advanced graduate seminar on "Science and Exploration of Phobos and Deimos" lead by Dan Britt and Carle Pieters. RISE, VORTICES, ISET, and IMPACT also participated. The seminar was broadcast on AdobeConnect and is recorded for future use. This seminar was extremely successful with large on-line audiences (831 live logins and, to date, 3973 ondemand viewings), excellent talks featuring the leading researchers in Phobos/Deimos science, and excellent questions and comments from the students and the on-line audience. This series showed the power of SSERVI scientific and telecommunication expertise in disseminating cutting edge science to a very wide audience.

ARM FAST group picture in front of the ARM mockup boulder. The FAST includes 4 CLASS Co-I's and 5 other SSERVI members.

CLASS Science:

Dr. Dan Britt (CLASS PI): Dan was named to the ARM FAST and also the New Horizons science team. The FAST work has started a number of related investigations including: (1) Research into the strength of boulders. (2) The strength of meteorite materials. (3) Structure of small asteroids. On-going research includes: (1) Space weathering products of volatile-rich asteroids including the possibility that the precursors of life can generated on small bodies. (2) The potential of asteroidal for radiation shielding. (3) Measurement of the density and porosity of meteorites. (4) Development and production of terrestrial analogs for meteoritic materials (prototypes of a CI analog were provided to three NASA centers and 3 ISRU investigations). Dan also gave an invited talk on asteroid regolith to the NASA AES planning group on August 4. 2015.

Dr. Humberto Campins: Since our last report, we produced five refereed publications and six conference presentations; three more refereed papers have been accepted for publication and three more are in preparation. We also assisted NASA's Asteroid Redirect Mission (ARM); H. Campins was selected as one of 18 members of the ARM Formulation Assessment and Support (FAST) team. H. Campins was invited by the University of Paris (Diderot) and the Paris Observatory to spend the month of May 2015 working in France on joint research projects with S. Fornasier, A. Barucci, C. Lantz and other colleagues. We have carried out, reduced and analyzed observations from four observatories, NASA's Spitzer Space Telescope, NASA's IRTF facility in Hawaii, the 10.4-meter Gran Telescopio de Canarias and the 3.5-meter Galileo Telescope.

Dr. Peter Brown: CLASS work has been an initial study and publication of data related to meter-scale impactors from US government sensor data. I have also been working on refinement of global infrasound measurement of large impactors from the International Monitoring System (IMS) together with a new graduate student of mine, Caroline Gi. My other work has mainly focused on meteoroid studies related to comet parent bodies and the tracking and recovery of meteorites by observing bolide trajectories (see picture in this report).

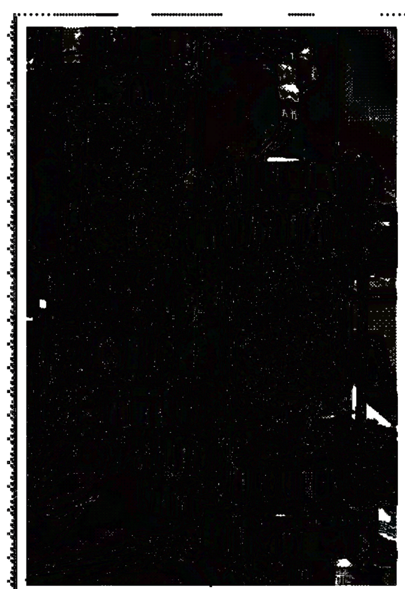
Ejecta produced during a microgravity impact in sand during the PRIME flight campaign.

Dr. Josh Colwell: We have carried out an experimental program to study the response of different types of regolith to impacts in microgravity, similar to that at the surface of a small asteroid or the Martian moons Phobos and Deimos. Experiments have been carried out in parabolic airplane flights in 2014 and we have been analyzing the data from those experiments during the past year. In addition, we have performed experiments in our 0.8-second drop tower facility at the Center for Microgravity Research at UCF. We have completed tracking ejecta and crater formation from the PRIME parabolic flight campaign and analyzed these data for publication in 2016. We have also developed a design for an improved PRIME payload for flight in 2016. We developed and delivered the hardware for the Strata-1 payload on the International Space Station, scheduled for launch in March 2016. This payload is designed to understand the mixing and sorting of different types of particles within asteroidal regolith in microgravity subject to minor vibrations such as thermal quakes and secondary impact cratering.

CLASS Co-I Dr. Guy Consolmagno SJ was named the director of the Vatican Observatory by Pope Francis.

Drs. Guy Consolmagno and Bob Macke: CLASS Co-I Dr. Guy Consolmagno SJ was named the director of the Vatican Observatory by Pope Francis (picture). Macke continued work on the density and porosity of lunar and Martian materials to aid interpretation of gravity data of the crust of the Moon and Mars The second project is the measurement of thermal properties of meteorites to model thermal properties of asteroid surfaces and interiors. The former project is done in conjunction with Kiefer, Irving, and Britt. This year, my role has been primarily data analysis from research visits by collaborators to work with the NASA Apollo collection and meteorites from the University of Washington and the private collector Naveen Jain. For the latter project, I am collaborating with Opeil, Consolmagno, and Britt. I have been measuring ordinary chondrite heat capacities using liquid nitrogen immersion, as well as theoretical modeling of OC heat capacities based on mineral composition.

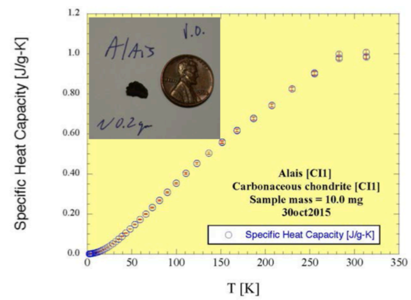
Dr. Adrianne Dove: Added to CLASS as a tenure track faculty hire, part of UCF's matching commitment to CLASS. Along with several UCF colleagues, I have been a science advisor on the Strata-1 payload (PI Marc Fries at JSC), a microgravity regolith experiment designed to explore the long-term evolution of regolith particle size distributions and stratification in a low-gravity environment. For this project, I lead the development of the hardware for the Strata-1 experiment chambers. This included a redesign of experiment chambers previously flown on parabolic airplane flights in order to provide different mechanics and better vacuum quality. Development of the payload also included the design of a new regolith compression mechanism for use during launch and landing. Strata-1 is slated to fly on the OA-6 launch in March, 2016 and remain aboard the ISS for approximately one year. We have developed proposals for several follow-up and complementary payloads, and hope to secure funding to build these payloads for parabolic, suborbital, or orbital flights. Another key project has been the development of a collaboration with the KSC Launch Services Program (LSP) Electromagnetic Compatibility (EMC) group to enable investigation of plasma charging



Strata-1 sample tubes ready for delivery for flight to the International Space Station. Top: Sample tubes with glass bead and crushed bead samples for calibration of numerical simulations.

effects. Through this collaboration, I was able to secure funds to enhance a vacuum chamber in my lab at UCF. Initially, this setup will be used to study the effects of spacecraft surface charging in the Earth's atmosphere (primarily to enable the SurfSat CubeSat mission). The chamber, however, is being designed to be able to reproduce a wide range of plasma environments (neutral plasma, electron beam, UV photoemission) and will have broader capabilities that will be used to explore spacecraft charging in other environments, charging of regolith surfaces, and other related effects.

Dr. Dan Durda: Work in Year 2 has been focused primarily on assisting in the science definition and design of the STRATA-1 regolith experiment for the International Space Station. In early 2014 NASA JSC received approval for a fast track process to design, develop, and fly an asteroid regolith experiment on the International Space Station within approximately one year. The project is led by Marc Fries (PI), Lee Graham (PM), and Kristen John (deputy PM); I was invited by Paul Abell to join the team as a science Co-I and have contributed primarily under the aegis of the UCF/CLASS SSERVI team. My contributions to the design of the experiment have focused primarily in the areas of (1) assisting in the selection/specification of the regolith simulant materials to be included in the four transparent cylindrical containers that comprise the experiment and (2) defining the image cadence for the experiment's GoPro cameras. Discussions on experiment design have been conducted via a series of weekly and bi-weekly Science Team and Payload Integration telecons.



The temperature dependent specific heat capacity of the of the CI carbonaceous chondrite Alais measured by CLASS Co-I Dr. Cy Opeil.

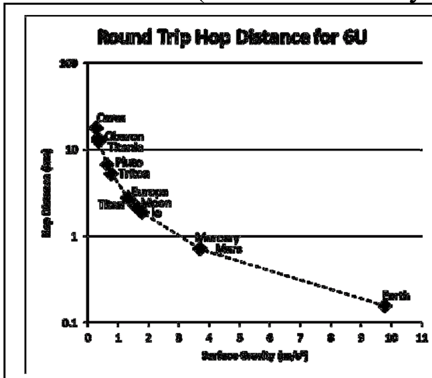
Dr. Chris Herd: The commissioning of the meteorite lab (including cold curation facility) in 2014 has led to ongoing, active use of the facility – primarily for the PhD work of Danielle Simkus which involves exploring new types of organic compounds in previously unsampled specimens of the Tagish Lake meteorite –as well as for other researchers worldwide. The uniqueness of the facility is only just becoming known; a manuscript describing the facility in press as of the end of 2015 in Meteoritics and Planetary Science. I also gave a presentation in the Phobos/Deimos seminar and participated in the sessions with my students.

Dr. Javier Licandro: Primary work was the analysis of size and thermal properties of Asteroids in Cometary Orbits determined using WISE data. Other projects included the development of the Primitive Asteroid Spectroscopic Survey (PRIMASS) aimed to obtain visible and spectroscopic data of primitive families that can produce primitive NEAS like Polanas, Erigones, Sulamities, etc. with the aim of characterize them and better understand the link between primitive NEAs and primitive families. I am part of the OSIRIS-REx Science Team as collaborator and I have been working in the Image Working Group together with CLASS Co-I Humberto Campins. We are preparing ourselves to produce and analyze the color maps that will be obtained with the OCAM cameras. With CLASS support I organized the 2nd Thermal Models for Planetary Science (TherMoPS II) meeting June 3-5 in Tenerife, Spain (see http://www.iac.es/congreso/thermopsii/), with the participation of more than 40 worldwide experts in the field. It was a forum that made an update of all aspects involved in the thermal modelling of solar system objects, from observations to theory, including laboratory work.

Dr. Marco Delbo: Continues his collaboration in spectroscopic observations of asteroids with team members Licandro and Campins to obtain mineralogical parameters for asteroid thermal modeling. He is responsible for the Gaia asteroid catalog; the Gaia mission of the European Space Agency (ESA) will survey the entire sky with a limiting magnitude of about 20 in the V-band. Gaia will observe about 400,000 asteroids and produce high precision astrometry and photometry. Delbo is in charge of Gaia spectrophotometric observations of asteroids in the wavelength range between 0.35 and 0.95 microns. He has also made significant contributions to thermal modeling and analysis of NEAs.

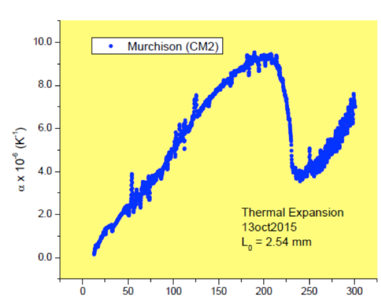
Dr. Yan Fernandez: Working on radar observations of NEAs including the characterization of their highly complex shapes in order to apply thermal modeling techniques. He is mentoring grad students Jenna Jones and Charles Schambeau. Jenna is working on thermal modeling of S-type asteroids and Charles is developing a thermophysical and chemical model of the comet 29P/Schwassmann-Wachmann.

Drs. Tom and Ashley Kehoe: Dust band modeling allows us to determine the cross-sectional area and size-distribution of dust particles associated with a given asteroid disruption and, furthermore, enables us to begin to reconstruct the physical properties of the regolith on the surface of the parent asteroid before its collisional disruption. For the older (several-million-year old) fully-formed dust bands, the size distribution of particles composing the band is much shallower than that measured for the very young (220 ky old) partial band that is still in the process of forming. The older bands yield a cumulative size distribution power-law index of 1.2, and the younger band yields an index >2.1. Our method of using young, still-forming partial dust bands to determine the size distribution at disruption allows us to describe a population of particles that is much closer to the original surface material and to better constrain the depth of the regolith on the surface of the original asteroid.



Hopping distance for a 6U cubesat on different planets with a 3U water tank (Metzger).

Dr. Phil Metzger: Metzger began working with Honeybee Robotics to develop small spacecraft (CubeSats or similar size) that refill with propellants by mining asteroids or icy surfaces on moons. Metzger developed the thermodynamic equations for steam propulsion systems in vacuum and performed modeling of the spacecraft performance on different planetary bodies for a variety of conditions. The work shows the concept is feasible for most solar system bodies including Europa or Titan where the spacecraft could hop several kilometers on one charge of water. Metzger also performed a new analysis of test data from regolith erosion experiments. The new analysis shows the erosion scaling relationships for near vacuum conditions (relevant to the pressure inside a rocket exhaust on a body in vacuum) cannot be simply adapted from the relationships in ambient pressure. Metzger also began developing an experimental apparatus to study the compaction of soil at the lunar poles and whether thermal cycling plays a significant role in the compaction observed at the more equatorial Apollo and

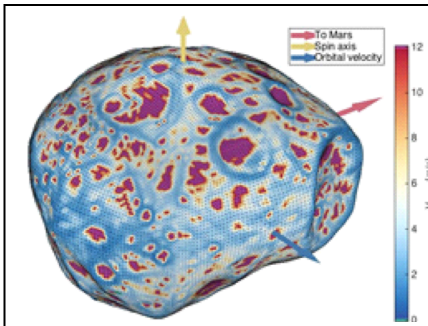


The temperature dependent coefficient of thermal expansion of the CM carbonaceous chondrite Murchison measured by

Surveyor landing sites. The experiment consists of several beakers of lunar soil simulant with steel weights on top to represent overburden at various depths in lunar gravity, and these are thermal cycled in an oven to derive a power law of soil settlement as a function of temperature swing, overburden weight, and number of cycles. This work is supporting NASA Ames for the Resource Prospector mission.

Dr. Cyril Opeil: Performed 44 heat capacity measurements (2-300 K) distributed across the following meteoritical classes: lunar (18), aubrite (2), howardite (1), diogenite (1), iron, as well as, ordinary (11), carbonaceous (8), and enstatite chondrites (2). Several thermal conductivity measurements (2-300 K) were made as part of the NASA Exploration Science Forum Conference presentation. Perhaps the most significant progress has been made in construction of the room temperature and cryogenic probe for measuring Young's Modulus. Hardware and software testing is expected to commence in mid-February 2016. At the request of one of my CLASS/SSERVI team members (Daniel Britt), I made thermal expansion measurements on several carbonaceous chondrites (CM2) to support ARM data requests. Although the results are preliminary, both Murray and Murchison show a very large increase of its expansion coefficient at approximately 225 K (plot in this report). Further measurements and data analysis are underway.

Dr. Cass Runyon: Leads the CLASS EPO program. Her report is included in Section III.



Minimum speed for lift-off into orbit on the surface of Phobos. Purple regions are where no lift-off is possible due to the concavity of the Phobos surface (Van wal & Scheeres, in prep).

Dr. Dan Scheeres: Dan Scheeres has participated in the CLASS SSERVI team by providing research seminars and contributing to the CLASS-sponsored Phobos and Deimos student course. In addition, research support has been used to perform research with Paul Sanchez on the nature of surface regolith with a focus on the role of cohesive forces in strengthening this material.

Dr. Patrick Schelling: Continued work on modeling the evolution of ion irradiation damage in silicates. We were able to show how diffusion of point defects differed between olivine and orthopyroxene, which may explain some of the differences in their weathering properties. What was done is to track the evolution of defects during the course of a molecular-dynamics simulation. The defects tend to evolve quickly at first, but then become trapped mostly is Coulomb-neutral clusters. This work includes the study of adhesion between dust grains, specifically silica and FeO (wustite) grains, as a function of chemical composition of the surface. We have found that water dissociatively adsorbed on grain surfaces can result in differences in the adhesive energy up to a factor of 3-4. In nanometer size grains, we have also found strong adhesion, more characteristic of ionic bonding rather than van der Waals bonding which is the usual description. This work may have significant implications for understanding the mechanical properties of rubble-pile asteroids, the adhesion of regolith grains on the surface of asteroids, and potentially even the formation of planetesimals. For example, we have demonstrated that it may be the case that Earth based experiments result in very different adhesive properties compared to what might occur in the space environment.

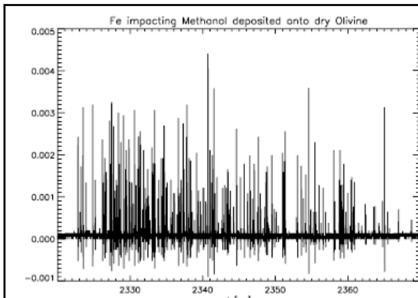
Dr. Larry Taylor: I have focused this on the role of the lunar simulant production, largely controlled through MSFC. This has led to the very disappointing conclusion that they have overseen SBIR contracts for >>$1M for the formation of lunar soil simulants with np-Fe, which are virtually worthless as such. This is addressed, along with the other numerous short-comings of the lunar regolith simulants, in a manuscript to be published in Planetary and Space Sciences. The effects of solar-wind proton bombardment upon the outer surfaces of soil particles on airless bodies, although the subject of several studies, has some problems with the proper selection and preparation of minerals. One of our grad students, newly from LANL where he was a technician on a beam line, has taken up the study of proton bombardment on lunar-type minerals. This has led to some unexpected results, which are the subjects of two manuscripts in preparation, as part of his dissertation. Part of his studies has been directed at the origin of chondrules, a subject that has been not resolved adequately, yet is at the core of the formation of meteorites.

Dr. Faith Vilas: We have been observing surface reflectance attributes of both near-Earth and main belt asteroids and small planetary satellites selected to address the presence of aqueous alteration and levels of space weathering that are apparent on different sizes and types of asteroids. Target selection is directed by the current state of the knowledge about the surface reflectance attributes of these objects at the start of CLASS. Larger diameter telescopes (e.g., the MMT 6.5-m telescope) are targeted to observe small-diameter (therefore usually low magnitude) objects.

Drs. Barbara Cohen and Robert Coker: Worked on thermal modeling of asteroid parent bodies, which may hold water and other resources for human explorers. This year, we explored the present state of the art for modeling of evolution of small bodies in the solar system. The goal was to determine if existing tools could model the thermochemical evolution of CM asteroid parent bodies with adequate fidelity. It was found that all existing methods were deficient in one way or another for this task. A second task was to determine if the Comsol code could be used to solve this problem. The next step will be to investigate the feasibility of modifying existing tools to this specific task; if it is infeasible, a code will have to be written from scratch.

II. Inter-team Collaborations

With the Institute for the Science of Exploration Targets: Thermal Evolution of ARM Targets. CLASS and Institute for the Science of Exploration Targets are working together to support ARM by investigating the surface thermal evolution of the ARM target 2008 EV5. Bottke and Britt will be co-advising a graduate student, Leos Pohl of UCF, on detailed orbital and thermal analysis of EV5 and how thermal evolution may affect the object's surface spectra, apparent volatile content, albedo, and strength properties.



Early results of the CLASS/ IMPACT collaboration looking at the impact generation of organics in volatile rich materials. The large number of mass lines point to numerous organic molecules created.

Institute for Modeling Plasma, Atmospheres and Cosmic Dust (IMPACT): Regolith Processes on Volatile-Rich Small Bodies. CLASS PI, Britt visited IMPACT in February 2015 for a LASP seminar, and to discuss and plan experiments addressing the physical properties of icy-regolith surfaces. The goal is to study how the chemical and impact environment on volatile-rich small bodies can produce conditions favorable for the syntheses of the organic precursors of life. Early experiments during the summer of 2015 are very promising (picture).

Remote, In Situ and Synchrotron Studies for Science and Exploration (RIS4E): Shielding Potential of Asteroidal Materials. RIS4E and CLASS are discussing joint projects and research on the use of asteroidal materials, particularly volatile-rich carbonaceous chondrites for shielding the reduce crew health hazards in long-duration spaceflight.

Center for Lunar Science and Exploration (CLSE): Radar Observations of Asteroids. CLASS and CLSE are working on an education module to explain the differences between actual pictures and radar "images" of asteroids. Too often even well-trained scientists make the mistake of thinking that radar imaging of an asteroid (which is becoming more frequent) is the same as a picture.

Evolution and Environment of Exploration Destinations: Science and Engineering Synergism (SEEED): Joint Seminar, Joint EPO Activities. SEEED and CLASS collaborated on the very successful graduate seminar *The Exploration of Phobos and Deimos*. This seminar had almost 5000 AdobeConnect logins between the live viewing and the views of the seminar recordings. This series showed the power of SSERVI scientific and telecommunication expertise in disseminating cutting edge science to a very wide audience. SEEED and CLASS have collaborated from the beginning of CLASS selection in their EPO activities, jointly funding Dr. Runyon as our combined EPO lead. This allows greater synergy in our EPO activities and extends our reach far beyond what each node could do on their own.

III. CLASS EPO Report

Dan Britt:

- CLASS sponsored a new trophy at the 2015 NASA Robotic Mining Competition at the Kennedy Space Center, awarded for innovation in granular mechanics.
- Other CLASS activities are in our full report under our EPO lead Cass Runyon.

Josh Colwell:

- I gave a one hour presentation to several hundred people at the Learning Institute for Elders (LIFE) continuing education program at UCF on November 17 including discussion of SSERVI exploration activities and our laboratory experiments.
- We provided tours of our lab facilities to high school and undergraduate students throughout the year, reaching approximately 100 students.
- We published an astronomy podcast, "Walkabout the Galaxy", aimed at the general public. Several episodes discussed the manned exploration program including SSERVI science and exploration goals. The average number of downloads per episode is a bit over 200.

Addie Dove:

- AAS CVD participant (March 2015)
- Presentation to several high school classes in KS via Skype (Apr 31)
- UCF Physics Day (Sept 3)
- International Observe the Moon Night (Sept 19)
- Lunar Eclipse event (Sept 27)

- TeachIn Day – Danielle Miller's classes at University High School (Nov 18)
- Knights Under the Stars events
- Walkabout the Galaxy
- Press coverage: Brendan Byrne CubeSat piece (WMFE), Fox35 News piece about CubeSats
- Advisor to the Lunar Knights – student group centered around the development of a robot for NASA's Robotic Mining Competition

Dan Durda:
- In September I began a VFX experiment inspired by the recent GoPro footage from Terry Virts' Space Station spacewalk (e.g., https://www.youtube.com/watch?v=--ysPOJepOw) combined with lighting reference from the Kaguya HD footage from lunar orbit (e.g., https://www.youtube.com/watch?v=Oy2L9Jti9Z4). The purpose is to be able to replicate the look of hand-held camera video for a variety of different space mission EVA scenarios (a near-Earth asteroid mission, etc.) for the purpose of popularizing exploration of Solar System bodies of relevance to SSERVI. I placed the video on my personal vimeo page and posted to the web forum for the software application that I used to produce the test: https://vimeo.com/140681196
  http://community.thefoundry.co.uk/discussion/topic.aspx?f=9&t=115792

Chris Herd:
- Bruderheim 55th Anniversary Event keynote: "The Bruderheim Meteorite" March 4, 2015
- NASA SSERVI Lecture "Phobos and Deimos: Properties of Meteorite Analogues" (1 hr) Nov. 16, 2015
- Interviews related to 55th anniversary of fall of the Bruderheim Meteorite (Edmonton Journal, Fort Saskatchewan Record)
- Promo interview for Science Summer Camps, Breakfast Television, April 14, 2015
- Provided multiple tours of the Meteorite Curation Facility
- July 23, 2015: Interview with CBC Radioactive (Edmonton local) about NASA discovery of Earth-like planet Kepler 542b
- Dec 16, 2015: Interview with Ivan Semeniuk (Globe and Mail) about the OSIRIS-REx asteroid sample return mission, and Canada's involvement in it; published same day, http://www.theglobeandmail.com/news/national/canadian-laser-system-begins-long-voyage-to-explore-asteroid/article27793658/
- Dec. 26, 2015: quoted by Tom Spears in Ottawa Citizen article on 2015: Looking Back, Year of the Close-Up; http://www.pressreader.com/canada/ottawa-citizen/20151226

Javier Licandro:
- Regular contributor to the weekly science podcast "Coffee Break" of the Instituto de Astrofísica de Canarias (http://vivaldi.ll.iac.es/proyecto/coffeebreak/)
- I made a presentation on the "Astronomizate 2015" course for public in Los Realejos (Tenerife, Spain) entitled "Misterios del Sistema Solar" (Mysteries of the Solar System) on July 1st.
- I make several interviews for local and national TV and radio stations. In particular I have been part of the documental "Desmontando a Plutón" (Deconstructing Pluto) for the Spanish TVE-1 channel program "Informe Semanal" (http://www.rtve.es/alacarta/videos/informe-semanal/informe-semanal-desmontando-pluton/3234721/)

Phil Metzger:

- Metzger served as a robotics judge at the 2015 NASA Robotic Mining Competition at the Kennedy Space Center. Metzger led a discussion of the judges, who awarded the trophy to Case-Western Reserve University for an innovative wheel design that compacts rather than disrupts soil as it drives, enhancing traction and reducing the risk of getting stuck. About 40 university teams brought robots to mine simulated extraterrestrial regolith.
- Metzger gave a keynote address at the kickoff of Project Regolight at the Deutsches Luft- und Raumsfahrt (DLR) center in Cologne, Germany. The project is developing technology to 3D-print buildings using only sunlight and regolith, and it is funded by the European Union's Habitat 2020 initiative.
- Metzger spoke at Space Week at the Museum of Science and Industry (MOSI) in Tampa, Florida, on "How Lunar Soil could Change the World."

Cass Runyon: CLASS Outreach Activities

Throughout the second year of the SSERVI grant, the SEEED and CLASS SSERVI Education Public Engagement (EPE) team was actively engaged in training pre-service and in-service educators from both formal and informal institutions across the country, working with students and engaging the public on SSERVI-related topics, particularly those being focused on by CLASS and SEEED.

During the first year (2014) we formed a core team of dynamic science educators, authors, artists and storytellers from around the country to help us develop engaging inquiry-based, hands-on activities using SSERVI data and resources. This dedicated team of educators met in August, 2015 to develop, test and redesign a set of formal lessons using current SSERVI data and imagery. Our EPE team is focusing on three areas using SSERVI content: 1) infusing arts into traditional science, technology, engineering and mathematics (STEM) lessons; 2) integrating formal, informal and out-of-school experiences to foster content retention; and 3) broaden audience reach to include ALL learners, especially those with disabilities. We continue to communicate and work with the core group of educators via Wiggio, an online collaborative tool and meeting site. Divided into teams (i.e., science, engineering, technology), the team has been actively testing and adjusting the SSERVI science and technology related curricula and activities in their respective education settings.

We are working with one undergraduate student and one part-time staff member who are Blind. They are helping to develop, review, and test SSERVI – related curricula and activities vetted by the EPE Core Team. Three tactile guides – graphics and related text – are in final draft. In addition to developing resources for the sight impaired, we are also actively working with a teacher who is Deaf and who works with students whose first language is not English. In addition to assisting with resource development, she is helping to develop a list of modifications and / or adaptations needed to ensure that we address Universal or Inclusive Design.

Among our highlights for the year was being able to participate in Camp Happy Days, a camp for children with Cancer. We shared a variety of hands-on activities and talked to the campers about space exploration. One very keen camper has the dream of working with NASA to explore rocks from other worlds (see Figure 1). He was full of questions and eager to hold the Moon (lunar education disk) for as long as he could!

Event / Activity	Date	Location	# participants	Grades	Underserved*
Charleston STEM Festival	02.07 2015	Charleston, SC	7500	Public	Yes

Cougars Basketball STEM Day	02.18.15	Charleston, SC	1600	4 – 8	Yes
Space Science: Exploring scale and small bodies	03.07.2015	Berkeley County, SC	15	4 – 8	Yes
Earth Science for Teachers Course – hybrid course for pre- and in-service	06.05-07.03.2015	Charleston, SC + online	12	6 - 14	Yes
Camp Happy Days	07.01.2015	Summerton, SC	10 200 campers	4 – 16	Yes
Space Night at Charleston Riverdogs	07.26.15	Charleston, SC	4000+	Public	Yes
Science Days – Waterton / Glacier National Parks	07.17-18.15	Wateron, Canada Glacier National Park	2000+	Public	Yes
SSERVI Workshop – Core TEAM	08.01-05.2015	Orlando, FL	32	4 -16 / +informal	Yes
Educator Workshop	08.29.2015	N. Charleston, SC	24	4 – 12	Yes
NASA at NASCAR	09.07.2015	Darlington Speedway, SC	5000+	Public	Yes
NASA Mission Design Course	Fall / Spring 2015	Charleston, SC & Huntsville, AL	120	UG	Yes
Geology of the Moon - Online course for in-service teachers around globe	Fall 2015	18 states + military	20	4 - 16	Yes
CLASS Seminars - hosted WebEx presentations on SSERVI science efforts	Jan – Dec, 2015	Orlando, FL and WebEx	40+	Science Team and public	Yes

VI. List any undergraduate students, graduate students, postdoctoral fellows that you have worked with or had major influence over during 2015

- Sean Wiggins, UCF undergraduate, asteroid regolith simulants
- C. Hawley, UCF undergraduate student, asteroid observation data reduction
- N. Komisarjesky, UCF, undergraduate student,asteroid observations
- Z. Landsman, UCF graduate student, asteroid Observations
- Caroline Gi, Western U graduate student, refinement of global infrasound measurement of large impactors
- Elizabeth Silber, Western U post-doc, optical observations of meteors generating infrasound
- P. Pokorný, Western U post-doc, Quadrantid meteoroid stream
- A. Abedin, Western U graduate student, Meteoroid stream orbital evolution
- Akbar Whizin, UCF graduate student, Center for Microgravity Research labs
- Stephanie Gibson, UCF graduate student, Center for Microgravity Research labs
- Julie Brisset, UCF post-doctoral researcher, Center for Microgravity Research labs and Strata
- Addie Dove, UCF post-doctoral researcher through July 2015, Center for Microgravity Research labs and Strata
- Kelly Lai, UCF undergraduate, Center for Microgravity Research labs and Strata
- Thais Lage, UCF undergraduate, Center for Microgravity Research labs and Strata
- Allyson Whitaker, UCF undergraduate, Center for Microgravity Research labs and Strata
- Alexandra Yates UCF undergraduate, Center for Microgravity Research labs and Strata
- Merritt Robbins, UCF undergraduate, Center for Microgravity Research labs and Strata
- Jeffrey Jorges, UCF undergraduate, Center for Microgravity Research labs and Strata
- Will Santos, UCF undergraduate, Center for Microgravity Research labs and Strata

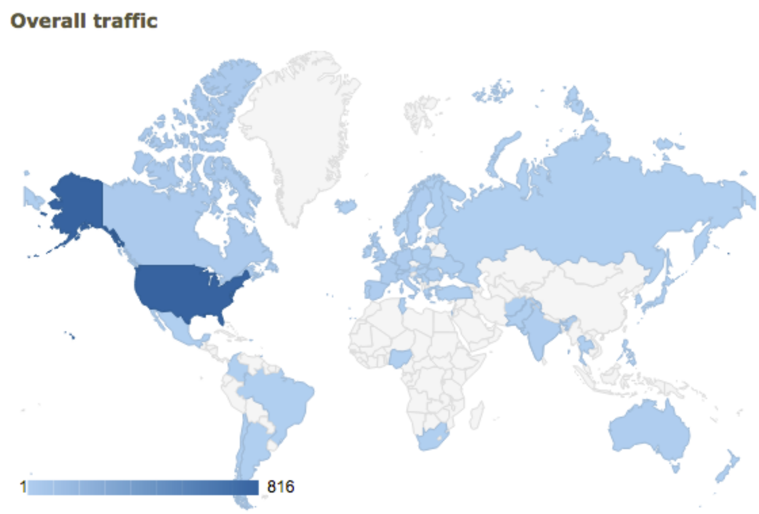
- Matthew Higgins, UCF undergraduate, Center for Microgravity Research labs and Strata
- Nadia Mohammed, UCF undergraduate, Center for Microgravity Research labs and Strata
- Leos Pohl, UCF Graduate Student, radiation shielding from asteroid regolith
- Janessa Buhler, UCF graduate student, plasma charging studies
- Jeffrey Strange, UCF undergraduate student, plasma charging studies
- Christopher Tiller, UCF undergraduate, plasma charging studies
- Danielle Simkus, U. Alberta PhD student, organics in Tagish Lake meteorite
- Nicholas Caslte, U. Alberta PhD student, petrology of Martian and eucrite basalts
- Cody Kuchka, U. Alberta MSc student, shock effects and trapped volatiles
- Cosette Gilmour, U. Alberta MSc student, ordinary chondrite metal and Tagish Lake water from the asteroid mining perspective
- Nicole Spring, U. Alberta Postdoctoral Researcher, cometary analogues and cold curation
- Ebberly MacLagan, U. Alberta, undergrad student, impact melt in core from the Steen River impact structure
- Wesley Chambers, UCF PhD student, exhaust plumes disturbing asteroid regolith.
- Sean Anderson, UCF undergraduate, lunar soil compaction for the Resource Prospectors.
- Christopher Noyes, Boston College undergraduate, developed measurement software for Young's Modulus experiments.
- William Tucker, UCF graduate student, experimental studies of space weathering
- Abrar Quadery, UCF graduate student, developing variable-charge model to model defect diffusion and interaction in metals and silicate oxides
- Baochi Doan, UCF graduate student, adhesion of mineral grains
- Lindsay Caves, U Tenn undergraduate, studies of Eucrites
- Scott Eckley, U Tenn undergraduate, studies of Eucrites
- Chris Wettlande, U Tenn Ph.D. Student, Effects of solar-wind proton bombardment of lunar highland regolith.
- Mariah Williams (blind), U Charleston undergraduate, Accessibility, assist with background research and content presentation at workshops and EPE events
- Quincy Hoffer, U Charleston undergraduate, Assist with content presentation at workshops and EPE events
- Natalie Pack, U Charleston graduate, Pre-service teacher, helped to develop and test SSERVI content-related activities; graduated and obtained a position in middle school and is actively integrating curricula into her classroom
- Sam Fink, U Charleston undergraduate, Assist with activities and questions from the public at EPE events.
- Caitlyn Mayer , U Charleston graduate, Accessibility, assist with background research and content presentation at workshops and EPE events
- Jenna Jones, UCF graduate student, thermal evolution of S-type asteroids
- George Hatcher, UCF graduate student, regolith simulants and microgravity
- Tracy Becker, UCF graduate student, accretion in ring systems
- Charles Schambeau, UCF graduate student, thermophysical/chemical model of the enigmatic comet 29P/Schwassmann-Wachmann

Appendix:

CLASS Seminars: 2015 Statistics

CLASS hosted 17 speakers in 2015. In addition to the in-person audiences, there were 2,611 views of the seminars from online viewers during the live streaming and of the recorded/archived talks. The viewers spanned the globe, with views coming from more than 55 different countries.

Views per individual speaker:
Phil Metzger- 33
Dan Scheeres- 465
Faith Vilas- 17
Jocelyn Dunn- 22
Justin Karl- 14
Elkins Tanton- 25
Gal Sarid- 4
Larry Taylor- 8
Dan Britt- 27
James Cantrell- 374
Roger Handberg- 6
Patrick Michel- 10
Charles Radley- 1157
Andrew Schuerger- 413
Jim Pawlek- 12
Serkan Saydam- 20
Scott Branting- 4



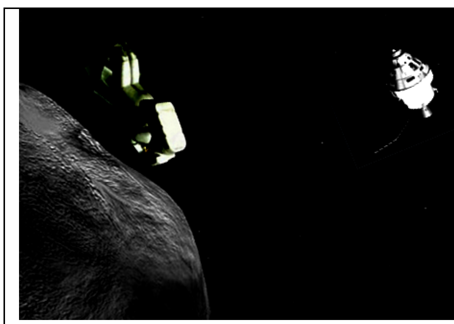
DREAM2 Annual Report Program Year #2: March 2015 to March 2016

DREAM2 PI team and Theme Leads: W. M. Farrell, R. M. Killen, G. T. Delory, J. S. Halekas, N. A. Schwadron, L. V. Bleacher

I. <u>DREAM2 Team Progress Report</u>

The *Wargo axiom* guiding SSERVI is 'Science enables Exploration and Exploration enables Science'. The DREAM2 corollary to this axiom is 'The Space Environment affect Human Systems and Human Systems affect the Space Environment'. DREAM2 studies this two-way interplay of exposed bodies placed in the space environment – including human-made objects.

To pursue an understanding of this two-way space environment-object interconnection, DREAM2 gathers over 30 internationally-recognized scientists under 6 themes that are common to airless bodies: Plasma interaction, exosphere formation, radiation interaction, surface modification, effects from extreme events, and human exploration (both robotic & human missions). The scientists interact and exchange ideas advancing concepts not just within these themes, but across these themes. Modeling, mission data, and laboratory experiments are all used to advance the new cross-theme concepts – which can even lead into the development of new mission concepts like those proposed by DREAM2 team members in PY2 to PSD and AES cubesat solicitations.



An illustration of the Orion spacecraft in the near-vicinity of the captured asteroid as planned under the ARM mission. DREAM2 team members modeled the effect spacecraft outgassing may have on the exposed body.

In the second year, the DREAM2 team continued its unique study of the space environmental effects at exposed bodies- with an emphasis on a universal approach (different bodies, different mass, different solar wind flow, etc). We outline our stunning research achievements over the past program year in this report - some of which are also presented on the DREAM2 website (http://ssed.gsfc.nasa.gov/dream/).

DREAM2's most critical element was the further development of the team's science tasks, and PY2 year has been very successful with publication of numerous new findings (> 15 publications, see Section 5), a set of prestigious awards for our early career scientists (see Section 4), and engaging the public and our NASA PSD & AES leadership on the human system-space environment interactions.

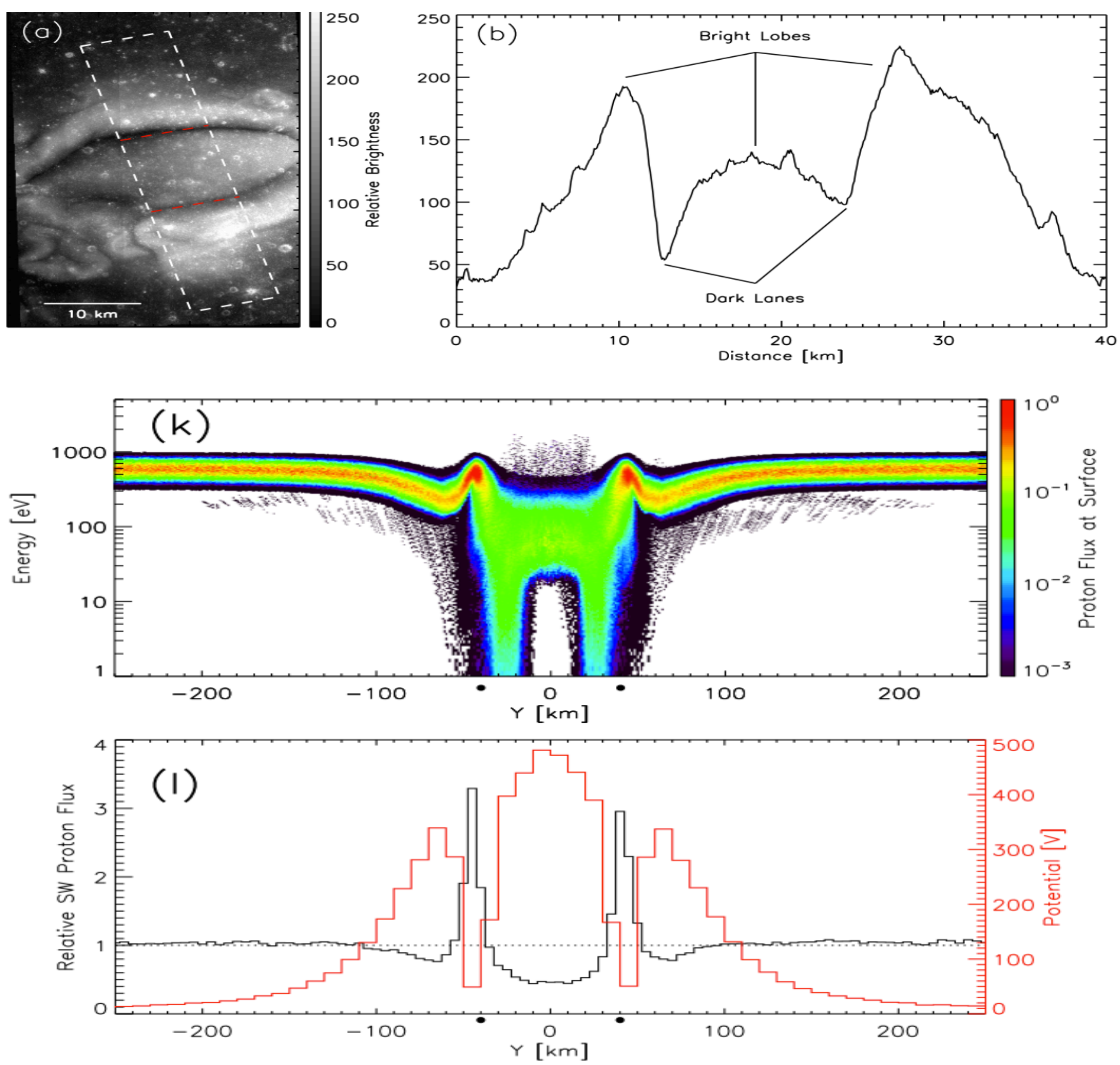
Theme 1: Plasma Interactions with Bodies on Large to Small Scales

Every body in our solar system interfaces with a plasma, either directly at the surface, or through the envelope of an atmosphere and/or exosphere. This interaction in part mediates the coupling between solar and magnetospheric influences and the planetary surface and sub-surface. Understanding these interactions not only lays the groundwork for future exploration, but also strengthens our grasp of fundamental processes, with implications for other planetary bodies throughout our solar system and beyond.

In the past decade, our understanding of the plasma interaction with airless bodies has skyrocketed, with new observations and modeling bringing a revolution in our understanding of the Moon in particular. Whereas we once thought of airless bodies as passive absorbers of the flow, we now understand that reflected and secondary particles in fact significantly affect a region many tens of thousands of km in extent, with disturbances extending far upstream from the surface. The DREAM2 team, with its combination of simulation experts and leading experimentalists, is now working to extend that understanding to bodies of all sizes and shapes, throughout the solar system. DREAM2 team members have made the following contributions in the past year.

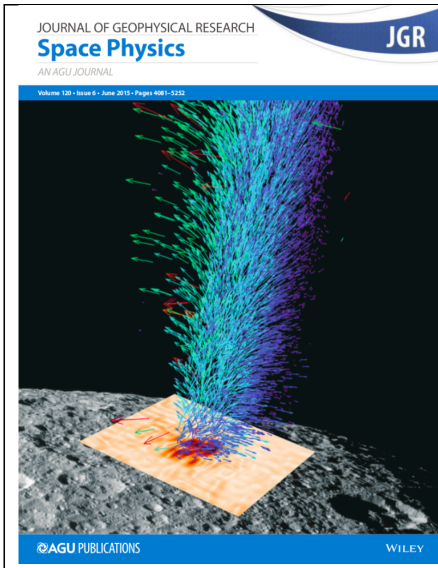
Plasma Interactions Topic	PY2 Advancements
Plasma Interaction vs. Body Size	Zimmerman et al. and Fatemi et al. simulations of plasma interactions with small-scale magnetic fields, Poppe/Curry Phobos simulations, Nordheim/Halekas 67P simulations, Harada/Halekas fore-moon studies.
Volatile/Plasma Connections and Exo-Ionosphere	Halekas et al. and Poppe et al. lunar exospheric ion studies, Sarantos LADEE Sodium/Potassium studies, Jordan & Stubbs breakdown weathering in lunar polar cold traps, Farrell/Zimmerman/Hurley spillage of lunar volatiles from cold traps, Farrell/Hurley solar wind implantation paper. Collier/Newheart studies using ALSEP SIDE ion measurements. Chi et al studies of pickup ion cyclotron waves.
Plasma Grounding and Electrical Interaction	Jackson & Farrell human system-plasma electrical interaction modeling. Stubbs & Hunt-Stone reanalysis of ALSEP CPLEE electron data.
Effects of Composition, Conductivity, Magnetic Field	Poppe and Fatemi swirl paper, Fatemi/Poppe/Fuqua lunar induction current modeling, Fatemi Gerasimovich paper, Sarantos et al. exospheric modeling.
Special Regions around Small Bodies	Zimmerman et al. tree-code simulations of plasma and surface charging at small irregular bodies, Poppe et al. non-aligned UV & flow paper.
Dust Around Small Bodies	Hartzell and Zimmerman plasma and dust simulations around small bodies, Poppe et al. Pluto dust paper.

We highlight a paper that exemplifies the DREAM2 spirit of exploring cutting edge science, collaborating across teams, and training young scientists. Poppe and Fatemi (a new young scientist on DREAM2) collaborated with researchers from U.C. Santa Cruz on simulations of plasma interaction with small-scale magnetic fields – not a new topic, but with a new twist. Delving into the intersection of plasma physics and geology, Poppe et al. were able to simulate the interaction for various magnetization geometries, and show that certain assumed magnetization distributions were better able to explain the observed swirl albedo markings at the famous Reiner Gamma feature, allowing us to use the observed space weathering as a new constraint on the magnetization of the crust, a quantity not uniquely determinable from magnetic field measurements from orbit.



Top row shows Reiner Gamma albedo marking and a transect.
Middle panel shows the simulated proton energy distribution reaching the surface. Bottom panel shows the electrostatic potential at the surface, and the proton flux. The reductions in flux create the bright lobes, a the increases in flux create the dark lanes of the albedo feature. From Poppe et al., 2016.

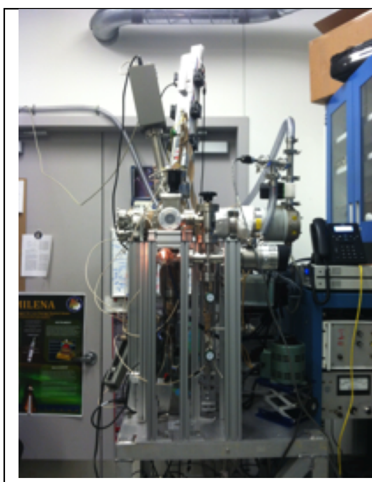
JGR Cover issue: Fatemi et al. (2015), Zimmerman et al. (2015), and Poppe et al (2015) examined the solar wind inflow into magnetic anomalies and found that the solar wind ion speed to the surface can be slowed by an ambipolar E-field that form within the anomaly retards ion motion. Some portion of the ion population is even reflected from the region. As a consequence, the associated ion sputtering yields in magnetic anomalies are vastly reduced, possibly creating reduced weathering. This work connects plasma to the extended geological environment to the surface in a rich and unique way. The Fatemi work was the cover of JGR-Planets.



Solar Wind-Magnetic Anomaly interaction. Fatemi et al., 2015 modeled the solar wind interaction with the Gerasimovich magnetic anomaly. Shown is the JGR cover of the reflected solar wind modeled via a hybrid plasma simulation.

Theme 2. Exospheres and Corona at Exposed Bodies

Team exosphere has made great strides in measuring and interpreting the lunar exosphere in the past year. Lunar exospheric argon was reported from LADEE and modeled by Grava et al. (2015) and by Hodges and Mahaffy (2015), and lunar exospheric sodium and potassium also measured by LADEE were linked to meteoroid streams (Colaprete et al., 2015). Colaprete et al. (2015) used observations of sodium and potassium emission lines from the Ultraviolet and Visible Spectrometer (UVS) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission to investigate the influence of meteoroid impacts and surface composition in determining the composition and local time dependence of the Moon's exosphere. The results showed monthly variations for both species, as well as an unexpected annual variation for sodium, which can be used to better understand the formation and evolution of exospheres on airless bodies. While the primary funding of these studies was via LADEE program, the model developments used to support the observations were funded by DREAM and DREAM2. Hence, these DREAM development efforts feed directly forward to the successful outcomes of the LADEE mission.



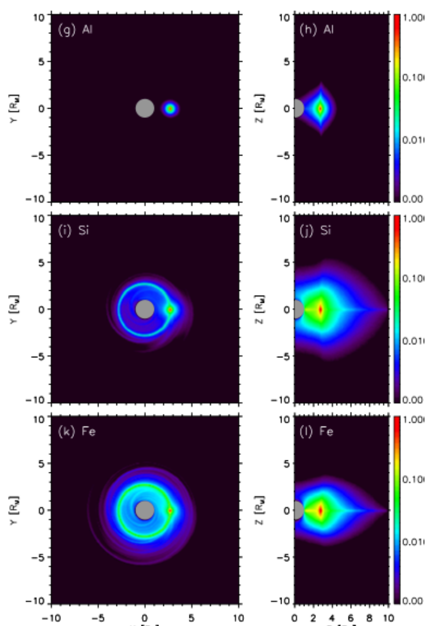
New Adsorption Laboratory Chamber: Regolith samples are cooled to Liquid He temperatures, there is molecular flow onto samples, and samples then heated via laser. Mass Spec monitors desorbed species.

In addition to measuring the lunar exosphere, laboratory studies were performed to understand the physical processes involved. McLain et al. (2015) obtained preliminary measurements of desorption kinetics on silicate 'smokes', which are analogs to micro-meteoritic impact vapor condensates. The development of a new adsorption chamber was driven by the need to get fundamental data in how molecules adsorb onto regolith-like surfaces and desorb under heating. DREAM2 funded parts of this chamber along with PSD/Solar System Workings. First light on this chamber was this October and results were presented at the *'Workshop on Space Weathering at Airless Bodies'* in early November (McLain, Sarantos, Keller, Nuth).

Theoretical work was done to determine the physical inputs for models. Hurley et al. (2015) fit the lunar surface temperature to an analytic function for exospheric modeling, and Killen studied pathways for breakup of simple molecules, leading to energization of the atomic fragments.

Other activity by Team Exopshere in 2015 include:

- Hurley et al, 2015 performed an analysis of the **contributions of impacts to the lunar water and hydrogen exosphere** using LAMP H_2 data and LADEE H_2O observations. Modeling reproduces the observations of H_2 if micrometeoroids release the H_2 from the regolith. However, the abundance observed is too high to be delivered by micrometeoroids. Therefore they proposed the possibility that solar wind H is released by micrometeoroids to produce the lunar H_2 exosphere. Water events detected by LADEE NMS are detected with the same frequency as impacts of mass > 3 g. They suggest these events are produced by the vaporization of water delivered by the meteoroids.
- DREAM2 co-I Dana Hurley also was the lead editor of the **Icarus special issue** on lunar volatiles, featuring 18 papers (including 3 papers from DREAM2 team members).
- DREAM2 co-I Andrew Poppe and MAVEN simulation expert Shannon Curry and Shahab Fatemi continue to examine the **sputtering from Phobos** and the formation of a heavy element-rich torus about Mars associated with the Phobos-released neutrals. In their 2015 paper (submitted JGR), they compare the sputtered vs impact vaporized portions of this torus.
- **LADEE UVS detection of a lunar nanodust exosphere**. DREAM2 members Glenar and Stubbs are collaborating with LADEE UVS team members Wooden, Cook and Colaprete on a study of weak continuum emissions detected by LADEE UVS. Light scattering models show that these measurements are consistent with sunlight scattering by an exosphere of very small dust grains. The results of this study are in the manuscript form and have been submitted for publication.



The neutral gas torus about Mars from Phobos-released neutrals (Poppe and Curry, 2014 and 2015).

Theme 3. Radiation interactions at Exposed Surfaces

Airless bodies like the Moon, the moons of Mars, or near earth asteroids (NEAs), are exposed to an energetic particle radiation environment that can significantly affect their surfaces. This environment comprises slowly varying, yet highly energetic galactic cosmic rays (GCRs) and sporadic, lower energy solar energetic particles (SEPs). These particles are energetic enough to penetrate the regolith of airless bodies: GCRs down to ~1 m and SEPs to ~1 mm. GCRs can eject energetic protons from lunar regolith, which can then be detected and mapped. GCRs and SEPs both deep dielectrically charge the subsurface regolith. SEPs, in particular, may create electric fields strong enough to cause breakdown (i.e., sparking).

In Program Year 2, the radiation team made significant advances in understanding the effect these energetic particles have on the surface, and even discovered a possible interaction between emitted energetic protons from water-rich surfaces.

Energetic proton albedo brightening over hydrated mineralogy Water on the Moon has been studied intensively for more than half a century [e.g., Lucey, 2009; Pieters et al., 2009]. Volatile accumulation in permanently shaded regions (PSRs) at the poles of the Moon has been suggested for many years, dating back to before the Apollo era [Urey and Korff,1952; Watson et al., 1961] and beyond [e.g., Arnold, 1979]. The Lunar Prospector Neutron Spectrometer (LP-NS) utilized neutron spectroscopy to probe the lunar regolith down to depths of ~50 cm, specifically showing the high abundance of hydrogen (H) or hydrogenous species at very high latitudes where epithermal neutron emission is suppressed [Feldman et al.,1998; Feldman et al., 2001; Lawrence et al., 2006; Eke et al., 2009]. While these regions show suppressed neutron emissions, the specific association with PSRs has not been fully established and remains an important objective. The Lunar Exploration Neutron Detector (LEND) on the Lunar Reconnaissance Orbiter (LRO) subsequently provided global maps of lunar neutron fluxes [Litvik et al., 2012].

Very recently, Schwadron et al. [2015] discussed a new technique for observing hydrated material at the Moon using the energetic proton albedo [Wilson et al., 2012; Looper et al., 2013; Wilson et al., 2015]. Until recently, it has been unclear how the energetic proton albedo could be used to infer compositional signatures of the regolith. However, a key signature of latitudinal dependence in the proton albedo (increased energetic proton activity with latitude) provides continuing support for albedo proton sensitivity to hydrated material.

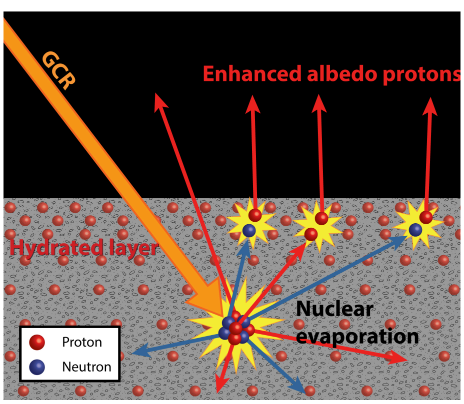


Illustration of the effects of a hydrated layer of lunar regolith. If a neutron collides with a hydrogen nucleus near the surface, the collision would yield an additional "tertiary" proton. In general, the interaction of secondaries from deeper in the regolith with the hydrated layer would create an excess of albedo protons.

The observed high latitude brighter albedo protons from a hydrated layer near the surface can be understood in terms of several steps: (1) GCRs penetrate the regolith, producing a large upward secondary neutron flux through nuclear evaporation of subsurface atoms heavier than H; (2) The collisions between upward neutrons and H in the hydrated layer causes forward scattering of protons, leading to an enhancement of albedo protons. Notably, the process requires the presence of H with a higher abundance near the surface. Otherwise, forward scattering of incident GCRs would suppress the flux of secondary protons.

Other radiation studies developed and advanced in PY2 are described in the table below.

Radiation Topic	PY2 Advancements
Dielectric Breakdown Across the Lunar Surface [Jordan et al., 2015]	During solar storms, airless bodies are exposed to solar energetic particles (SEPs). These particles are energetic enough to penetrate the regolith to ~1 mm and cause deep dielectric charging. In cold locations, the resulting charging may generate electric fields strong enough to cause dielectric breakdown (sparking). We have found that, in permanently shadowed regions, the fraction of gardened regolith affected (i.e., melted or vaporized) by dielectric breakdown may be comparable to that affected by meteoroid impacts [Jordan et al., submitted to *Icarus*; see also Jordan et al., 2015a, 2015b].
First directly observed longitudinal variation of radiation dose rate for a large CME event at 1 AU [Joyce et al., 2015].	Solar storm energetic particle radiation dose was obtained from three different longitudinal positions in the heliosphere, which shows a large increase in dose when an observer position is directly connected to the interplanetary shock front. Such studies on positional dependence of SEP outflow relative to the solar storm front will feed forward to assessing the radiation hazards to astronauts and avoidance of said hazard.
GSFC's Community Coordinated Modeling Center (CCMC) work on SEP modeling [Zheng et al.]	Modeling studies of energetic particle creation in plasma shocks at they propage outward to 1 AU. Improved coupling of SEP events to propagation models. Better-connect the physics of the interplanetary plasma shocks emitted during CMEs to the generation of energetic particles. An understanding on the creation of these hazardous energetic particles will feed forward to better warnings of their incidence during missions.
Evolution of ICMEs during propagation [Winslow et al., 2015, 2016]	Using multi-point spacecraft observations of interplanetary coronal mass ejections (ICMEs), we study their propagation and evolution in the inner heliosphere in order to better predict their influence on planetary environments. In Winslow et al. [2015], we cataloged ICME events observed by the MESSENGER Magnetometer between 2011 and 2014 and presented statistical analyses of ICME properties at Mercury. In addition, using existing data sets of ICMEs at 1 AU, we investigated key ICME property changes from Mercury to 1 AU. We found good agreement with previous studies for the magnetic field strength dependence on distance, and we also found evidence that ICME deceleration continues past the orbit of Mercury. This study leads to a greater understanding of CME and shocks, and the potency of these storms in creating energetic particles that affect humans.
Updates to the Virtual Energetic	Enhanced capability of VEPO. Created Multi-Source Spectral Plot, Scatter Plot, and Ratio Plot services now provided for energetic particle data from

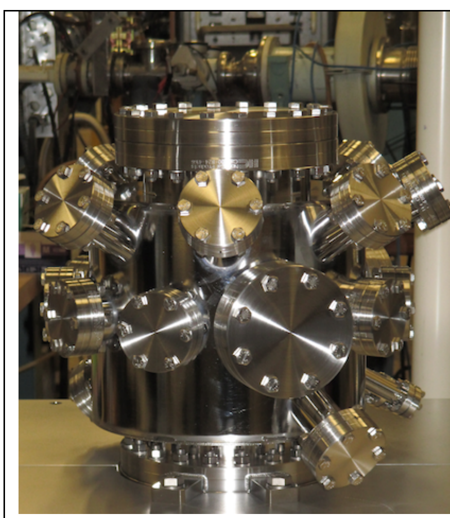
Particle Observatory (VEPO) [Cooper].	operational inner heliospheric spacecraft (ACE, Wind, SOHO, Stereo A/B) and legacy missions (Helios 1-2, IMP-8, Pioneer 10-11, Voyager 1-2, Ulysses). Full coverage for H and/or He ions, partial to full coverage for H – Ni ions. New abilities also include: (1) Inter-comparison of flux spectra from different spacecraft and instruments allows checking of relative calibrations for overlapping energy coverage. (2) Mission-duration average flux spectra can be used to model long-term space weathering of planetary bodies in the inner and outer solar system. (3) Multiple spacecraft spectral H-Ni response to large scale SEP eventsDual channel fluxes can be sequentially searched for special features, e.g. Fe/He SEP events, energy dispersion in low vs high energy electrons. VEPO collaborates with DREAM-2 in providing these data exploration services and in receiving feedback guiding development of future VEPO services.
Solar Modulation of the GCR Lineal Energy Spectrum [Zeitlin et al., 2016]	The long period of CRaTER observations allows us to study the evolution of these spectra as a function of solar modulation. As solar modulation increases, the total flux of GCRs decreases, and lower-energy ions are preferentially removed from the spectrum of ions that arrive in the inner heliosphere. These effects lead to variations in the Linear Energy Transfer spectrum, which is used to determine dose, dose equivalent, and risk to humans in space. The results are also of interest in the context of the DREAM2 project, which advances understanding of the galactic and solar radiation environments at the target bodies (including the Moon), emphasizing material interaction/reactions due to incident high energy particles. Understanding the LET spectrum and its evolution with time is important for characterizing the radiation environment and helps investigators understand the effects of high energy particles on target bodies. This work will be presented at the upcoming HRP meeting in Feb 2016.

Table: Radiation-oriented DREAM2 studies in PY2.

Theme 4: Surface Response to the Space Environment

As the harsh elements of space, like impactors and plasma, interact with the surface, their energy leaves a modifying signature on the surface structure. For example, space plasmas will disrupt the regolith crystal structure in the first 100 nm, creating defects that can trap solar wind protons and 'hopping' water or OH on the airless body. Radiation alters the surface by creating streaking defects and charge buildup which also may be sites for solar wind hydrogen trapping.

To test this, DREAM2 is completing the building of a dual-irradiation lab experiment in GSFC's radiation facility. We will first irradiate a sample surface with high energy radiation (> 1 MeV) to create defects in the material, then perform (under the same vacuum) a second irradiation of the sample by 1 keV D_2 or protons that simulate the solar wind protons. We will determine if the



Chamber placed at end of beam line for sample dual irradiation experiments.

additional **defects from the high energy radiation traps H (or D) and creates OH (or OD)**. The beam line is complete and the team is currently placing their newly procured chamber (see adjacent figure) onto the line (Loeffler, Hudson, McClain, Keller).

Other surface interaction studies include:

- **Hydrogen diffusion in a defected regolith.** Summer Intern Vince Esposito from Univ. of South Carolina worked with DREAM's Farrell in integrating TRansport of Ions into Matter (TRIM) code results into an existing hydrogen diffusion model developed in PY1 of DREAM (and published Farrell et al., 2015). The objective was to create a more realistic distribution of activation energy representative of a surface that has been damaged by space plasmas. The diffusion of solar wind implanted H was then modeled using the damaged surface, now having a population of high-retention trapping sites. The work was presented at thev *'Workshop on Space Weathering at Airless Bodies'* in early November (Esposito, Farrell, Zimmerman)
- **Neutral Hydrogen emission from the lunar surface.** In the lab, a GSFC team (McLain, Keller, Collier) are examining solar wind-like 1 keV proton interactions with lunar-like surface material, demonstrating that a surprisingly large fraction of the incoming ions convert and backscatter as energetic neutral hydrogen. They leave the surface at energy far greater than simple thermal energy –suggesting these H's do not dwell in the surface and undergo numerous collisions but instead are immediate scattered from the first nucleus they encounter.
- **Transport of lunar polar crater volatiles to topside regions via impact vaporization and plasma sputtering.** A model of the removal and transport of volatiles from lunar polar crater floors was published this program year, demonstrating that impact vaporization and sputtering are continually weathering crater floors and liberating volatiles to topside regions adjacent to the craters (Farrell, Hurley, Zimmerman).
- **Orion water outgassing and water retention on the asteroid boulder.** DREAM2 investigators (Farrell, Hurley, Zimmerman) submitted a paper to Icarus on the Orion-asteroidl body interaction expected during the ARM mission. Water may be retained on the asteroid surface, depending upon the defect character, maturity, and composition of the boulder. Estimates of the Orion water retention levels were provided.
- **Oak Ridge Mutli-charged ion sputtering on CaS surfaces** (Meyer, Bannister, Hihazi)**.** The lab team at ORNL bombarded CaS substrates with solar wind relevant multi-charged ions to examine the sputtering yields. On Mercury, very hot Ca has been observed (as reported by DREAM2 co-I Killen) which is believed to be associated with a possible exothermic reaction providing energy to dissociating products. The ORNL study begins to examine these effects in a lab environment.
- **Dust cohesion.** Dust expert J. Marshall has been investigating how dust and sand respond to transport forces, abrasion, tribocharging, and cohesion in airless or near airless Solar System environments with relevance to understanding fundamental physical processes as well as the response of airless body surfaces to contacts with astronauts or mechanical objects. Some controversial results have been found and are to be submitted to the journal Planetary & Space Sci. in early 2016.

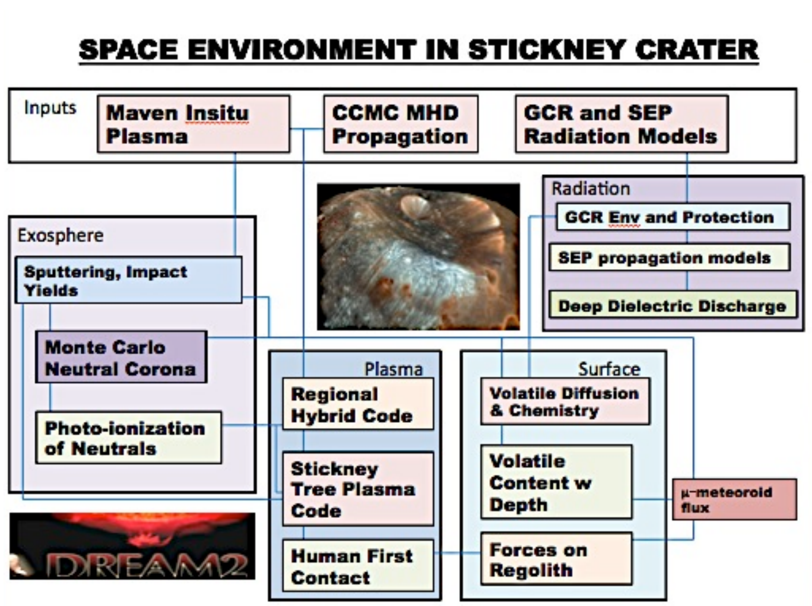
Theme 5: Integration and Extreme Events

In the upcoming last three years of DREAM2, the team plans to have a coordinated modeling efforts on the effect of extreme environments at small bodies and the Moon. This effort is called the DREAM2 Extreme Environment Program (DEEP). In this program, our models will be integrated to be run in a given sequence on a common event. This activity is similar to our 2010 SSLAM (Solar Storm- Lunar Atmosphere Model) effort under DREAM.

The three DEEP studies are 1) The effect of a solar storm at an exposed small body, 2) The space environment in Phobos' Stickney Crater, and 3) Human 'first contact' with a small body/NEA. This past year, the decision was made to proceed with a study of the space environment at Phobos and Stickney Crater (SEinSC). We spent the fall of 2015 laying out what such a study would look like including an information flow diagram (see below), showing how spacecraft and model plasma data flows down to the various models, how models are cross-connected and how model output information is exchanged.

Our plan is to hold a dedicated intramural workshop in the third week in April 2016 to show new results and fine-tune the cross connections.

Progress made so far: Fatemi's hybrid simulation of solar wind influences and effects at Mars has been developed. Model output will feed forward to a particle in cell code developed by Mike Zimmerman of Phobos itself, where the detailed sheath and wakes at the body can be modeled as a function of plasma conditions in the Martian tail. We have access to MAVEN data and GSFC's Community Coordinated Modeling Center (CCMC) possesses model CME events to Mars (used previously for comparisons with MAVEN data).



System-Level Block Diagram of the **'Space Environment in Stickney Crater'** Modeling Study

Theme 6: Mission and Exploration Applications

DREAM2's team continues to have broad and deep involvement in both SMD and HEOMD missions and studies. The most active involvement includes:

The Lunar Atmosphere and Dust Environment Explorer (LADEE). LADEE concluded operations in April 2014 and continued on in an extended data analysis phase through Oct 2015. DREAM2 Co-Is Colaprete, Delory, and Elphic all continued to be involved in the LADEE mission during this phase. Rick Elphic was the project scientist; Greg Delory was the Deputy project scientist, and was responsible for submission of the final derived data products to the PDS. A. Colaprete completed data submission for the UVS instrument. DREAM2 Co-Is Halekas, Poppe, Hurley, Stubbs, Sarantos, and Glenar continued to work with LADEE as Guest Investigators through the end of the data analysis phase.

Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS). As LADEE Guest Investigaotrs, DREAM2 Co-Is Halekas and Poppe have sustained a productive collaboration between LADEE and ARTEMIS. Along the way they have pioneered unique methods to support the interpretation of LADEE data using coincident measurements of lunar pick-up ions and the lunar plasma environment. Poppe has been using ARTEMIS data of pick-up ions to assist in understanding the currents levels in the LADEE/LDEX dust current system – to differential pick-ion currents from dust currents. Halekas has also used ARTEMIS pick-up ion observations to assist in the LADEE/NMS sensing of this component in its ion mode. A paper has been written in this joint ARTEMIS-LADEE analysis. These measurements have had measurable impact on both LDEX and NMS data processing. Hurley, Halekas et al have used ARTEMIS data of solar wind helium ion (alpha particle) flux to correlate with the LADEE/NMS and LRO/LAMP detection of surface-emitted exospheric helium. The correlation is stunning revealing that the helium exosphere is mostly solar wind driven, but with a possibly smaller geological residual. Additional work by DREAM2 Co-I Delory is using two of the ARTEMIS spacecraft in a study of induced magnetic fields at the Moon. This work also involved significant graduate student involvement (H. Fuqua), who won the outstanding student poster award at the 2015 SSERVI forum (see Section IV).

ARM Mission. DREAM2 members continue to be involved in ARM studies through investigations into astronaut charging. DREAM2 member Joseph Nuth is a member of the ARM Formulation, Assessment, and Support Team (FAST). The DREAM2 team has a paper in submission to Icarus on the Orion-Asteroid gas interaction.

Resource Prospector (RP). With FINESSE team members, DREAM2 co-is Elphic and Colaprete are instrument leaders of the HEOMD-funded RP mission to explore and prospect the lunar polar regions for volatiles. DREAM2 has contributes to this effort by provide models of volatile transport and redistribution that identify locations where RP might prospect. Models of rover wheel charging are also applicable to the RP rover system. The wheel charging model was presented at the recent lunar *Polar Regolith Workshop* (a SSERVI Workshop without Walls) held by SSERVI in early December 2015.

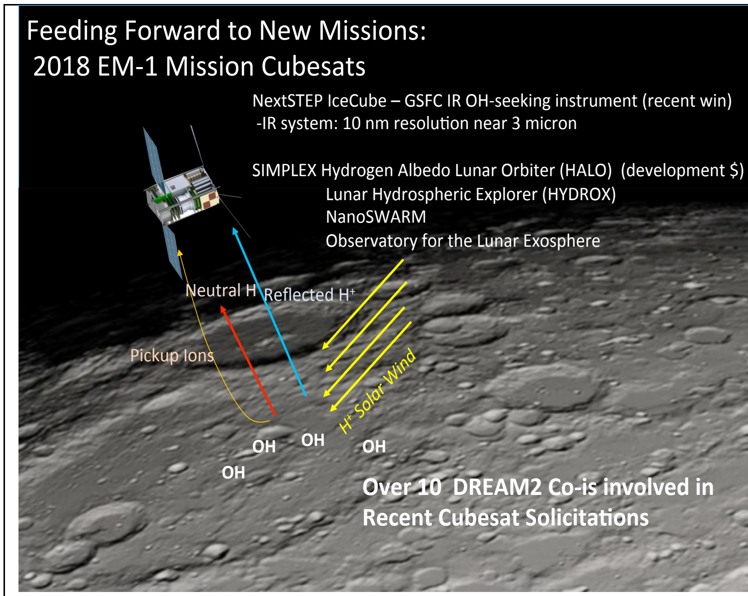
OSIRIS-REx. DREAM2 team member Joseph Nuth is the deputy project scientist on OSIRIS-Rex. Team member Marshall is the leader of the OSIRIS Regolith Working Group (RWG) and his dust cohesion work (described above) has direct implications on regolith stability anticipated at any small asteroid, including Bennu.

LRO. DREAM2 team members continue to support LRO. DREAM2 co-is Keller is the Project Scientists on the LRO Project Science team and there is continual DREAM2/LRO discussion on the latest finding especially on volatiles. Team member Nathan Schwadron is the

PI of the CRaTER instrument on LRO, with Andrew Jordan as part of the CRaTER science team. Dana M. Hurley remains a Co-Investigator on the LRO LAMP instrument. Team member Andrea Jones continues to support EPO on LRO. Tim Stubbbs continues his Guest Investigator role with the CRaTER team.

Additional Discovery and other mission proposals. Many DREAM2 Co-Is have had significant involvement in emerging mission proposals ranging from Discovery to cubesat-class that involve the physics of small-body/solar wind and plasma interactions.

Team members Poppe and Delory were Co-Investigators on the Discovery-class PADME mission to study Phobos and Deimos lead by ARC team members Colaprete and Elphic.



In 2015, DREAM2 team members were actively involved in lunar cubesat missions under the NextSTEP and SIMPLEX programs.

Cubesats. DREAM2 team members were very actively involved in new lunar mission concepts using cube-sats – especially those released during the 2018 EM-1 mission. Co-I Clark was the science PI of the awarded Lunar Icecube cubesat mission headed by Morehead State University and funded under the AES NextSTEP program. DREAM2 team members also submitted numerous strong cubesat concepts to PSD's SIMPLEX solicitation, including the Hydrogen Albedo Lunar Orbiter (HALO) concept (Collier, Keller, Farrell, Vondrak) that was awarded development funding, the Lunar Hydrospheric Explorer (HYDROX) proposal (Cooper, Stubbs, Sarantons), NanoSWARM (Poppe, Fatemi), and Observatory for the Lunar Exosphere (OLE) (Sarantos).

Team members at GSFC lead (Collier, Vonrak, Keller, Farrel, Clark) have also been examining the feasibility of a tethered cubesat to obtain 2- point radial measurements.

DREAM2 Co-I Clark continues the lead the community the Lunar Cubesat workshops which are has held annually over the last 6 years. These efforts are specifically designed to enable the community in anticipation of planetary cubesat proposal calls, like the recent SIMPLEX solicitation.

Team member Dana Hurley, as leader of the Friends of Lunar Volatiles group, contributed to exploration efforts by developing and submitting **a white paper on lunar polar volatiles** to the leadership of HEOMD – this to inform on the current state of knowledge.

II. Inter-team Collaborations

DREAM2 team members are in continual contact and collaboration with other SSERVI teams, science mission team, and Exploration architecture teams. Examples of DREAM2 interactions with other SSERVI teams include:

VORTICES: Strong collaborating work on solar wind/body interactions, volatile interactions, and Orion/asteroid interactions and lunar pits. Strongest collaborations with individuals like Zimmerman, Hurley, Bussey, Orlando, Hibbitts.

RISE4: Strong collaborating work on lunar pits, with the RISE4 field team providing lidar input to pit environment models shared by DREAM2 and VORTICES. Work with RISE4 team to pursue opportunities to architecture, design and build future exploration-oriented field instrumentation for astronaut use.

IMPACTS: PIs Hornayi and Farrell co-lead the SSERVI Dust and Atmosphere Focus Group. Strong cross-team collaboration including post-doc opportunities for students, like A. Poppe who did his thesis work under CCLDAS and is now a key DREAM2 team member. DREAM2 modelers working with IMPACTS modelers on magnetic anomalie studies.

FINESSE: We share co-is in Colaprete and Elphic, who under FINESSE perform field studies for their Resource Prospector mission, while DREAM2 provides supporting modeling studies on wheel-regolith interactions and volatile transport modeling.

III. Public Engagement Report

Summer 2015 marked another successful undergraduate internship program, with DREAM2 scientists at GSFC hosting four students, including one from DREAM2 partner, Howard University. In addition to completing their research projects, the students participated in monthly team meetings, tours of GSFC facilities, and a heliophysics boot camp. At the end of the summer, they presented their completed projects through poster and oral presentations that were open to the entire GSFC community and their families. While at GSFC, two DREAM2 interns were named John Mather Nobel Scholars via a competitive process. The program awards travel allowances towards the cost of presenting research papers at professional conferences. The two students also continued their DREAM2 research into the academic year.

The DREAM2 education and public engagement team implemented the Dream2Explore Educator Professional Development Workshop, which brought 23 middle school educators to GSFC for an in-depth week of hands-on activities, discussions, presentations by five DREAM2 scientists and others, tours, and networking opportunities with DREAM2 scientists. Content focused on SSERVI target bodies: formation, comparing/contrasting structure and composition of surfaces and exospheres, effects of space weather, engineering design challenges, NASA's current plans to explore asteroids and the "Journey to Mars". 100% of the participants agreed that they acquired activities that they will use with their students. 91% agreed that they feel confident in implementing the activities and that they acquired a new understanding of planetary science and exploration that will be valuable when working with their students.

Participant quotes: *"The workshop improves my class and the kids' learning. That's what it's intended to do!"; "I gain useful information for the classroom and feel comfortable using it since I have done it."; "I really value learning new material as a teacher – if I learn new things… the students learn new things. I learned a lot here – Thank you!"; "This is the only experience that as a teacher I have an opportunity to connect with scientists."*

DREAM2 team members also shared information about DREAM2 and SSERVI at public engagement events, such as the University of Maryland's annual Maryland Day event, International Observe the Moon Night at the Andrews Air Show, and GSFC's open house "Explore@NASA Goddard". Each event drew crowds in the tens of thousands.

IV. Student/Early Career Participation and Associated Awards

2015 Undergraduate Summer Interns
Anastasia Newheart, St. Marys (1)
Keenan Hunt-Stone, Howard Univ. (2)
Vince Esposito, Univ of South Carolina (3)
Tatiana Tway, Delaware Valley Univ.
Huong Vo, Univ. of Washington

2015 High School Summer Interns
Aparna Natarajan, Wooton HS
Zoe Himwich, Bethesda-Chevy Chase HS

Graduate Students
Heidi Fuqua, UCBerkeley (4)
Colin Joyce, U. New Hampshire

DREAM2 Post-Docs
Shahab Fatemi, UCBerkeley
Reka Wilson, U. New Hamphire

DREAM2 Student awards:
(1) A. Newheart: John Mather Nobel Scholars Award
(2) K. Hunt-Stone: John Mather Nobel Scholars Award
(3) V. Esposito: Robert H. Goddard Memorial Scholarship from National Space Club
(4) H. Fuqua: Outstanding Grad Student Poster Award at SSERVI Exploration Science Forum

Remote, In Situ, and Synchrotron Studies for Science and Exploration (RIS^{4}E)—2015-2016 Annual Report

1. Team Project Report

The RIS^{4}E team is organized into four distinct themes, which in addition to our E/PO efforts, form the core of our science and exploration efforts. Results from the second year of RIS^{4}E activities for each of the four themes are discussed below.

Theme 1: Preparation for Exploration: Enabling Quantitative Remote Geochemical Analysis of Airless Bodies. The major activities in this theme have focused on (1) synthesis and characterization of new mineral standards, (2) acquisition of mid-IR (MIR) emissivity and temperature-dependent visible/near infrared (VNIR) reflectance spectra in simulated lunar/asteroid environments, (3) testing and validation of advanced light scattering and radiative transfer models for quantitative interpretation of remote spectral data, and (4) remote sensing analyses of SSERVI Target Bodies. After several months of testing different plagioclase synthesis methods, we decided that our future spectroscopic studies would be better served with high quality natural specimens. Syntheses of pigeonite were successful, although the products are fine grained (5-15 µm). These samples are suitable for VNIR spectral analyses but we require coarser (~100 µm) samples for MIR analyses, which are being prepared (Schaub et al., 2016).

We have also been acquiring spectra of minerals in a simulated lunar/asteroid environment (SLAE). The bulk of this work has been carried out by graduate student Katherine Shirley at Stony Brook, who has been focusing on understanding the effects of particle size on infrared spectra of common silicate minerals in SLAE (Figure 1; Shirley et al., 2016).

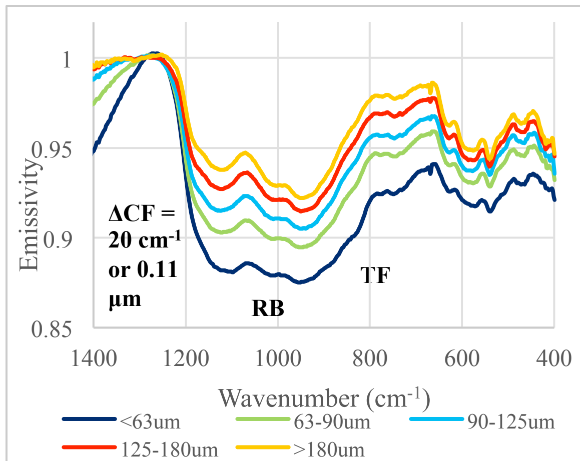


Figure 1. SLAE spectra of anorthite. Note the shift in Christiansen Feature (CF) with grain size, as well as the decrease in Reststrahlen Band (RB) and transparency feature (TF) minima with grain size.

The PI's research group at Stony Brook has also continued its efforts to develop VNIR and MIR scattering models making use of a coupled T-matrix/Hapke code to better understand the physics of light scattering in laboratory and remotely sensed spectra. Hardgrove et al. (2016) use a hybrid model to explain the odd spectra of microcrystalline quartz. Recent work by graduate student Carey Legett has also used a similar model to better characterize the effects of nanophase metallic Fe on VNIR spectra of silicates (Legett et al., 2015). Finally, our team has been engaged in a number of remote sensing studies, including analyses of lunar swirls (Glotch et al., 2015) lunar olivine-rich regions (Arnold et al., 2016), and near-Earth and main belt asteroids (Burbine et al., 2016).

Theme 2: Maximizing Exploration Opportunities: Development of Field Methods for Human Exploration. The major activities in Theme 2 involved our second 10-day long field excursion to the 1974 lava flow on the flanks of the Kilauea volcano on the Big Island of Hawaii. This year, the team conducted several geologic field investigations to test operations procedures that future astronaut geologists would use on one of the SSERVI target bodies. The operations team included astronaut Rick Mastracchio, Dean Eppler of Johnson Space Center, and postdoc Debra

Hurwitz of NASA Goddard Space Flight Center. The EVAs simulated by the crew were supported by four instrument teams, who provided field data using a handheld multispectral IR imager (Figure 2), a portable XRD, a handheld XRF, and a portable LiDAR. Work this year was also supported by kite-based aerial imagery, which provided local geologic and topographic context. As with our previous field season, a major goal of this work was to evaluate the use of different handheld or portable scientific instruments in field and to determine their best use practices in realistic ops environments. A series of papers detailing the instruments' calibration, use in the field, and scientific results is currently in preparation.

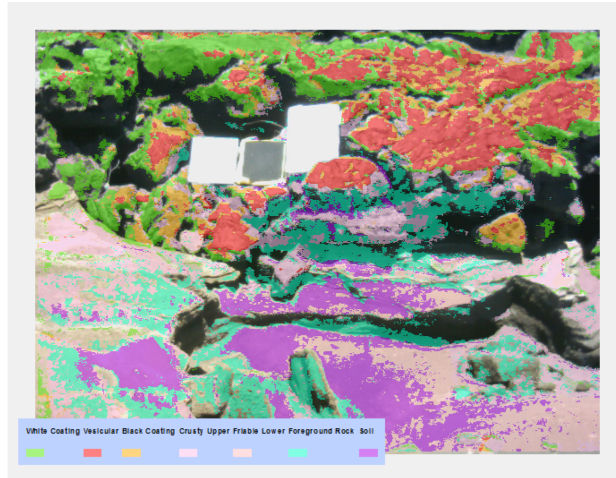


Figure 2. IRspectral classification map of basalt flow.

Subsequent to the 10-day field excursion, samples collected in the field were returned to Stony Brook University for MIR and VNIR spectral analysis. Samples are now at Goddard for laboratory XRF analyses. An abstract describing our field work will be presented at the 2016 Human Research Program Investigators' Workshop (Bleacher et al., 2016).

Theme 3: Protecting our Explorers: Understanding How Planetary Surface Environments Impact Human Health. In our second year of work, we have continued testing the toxicity and reactivity of lunar simulants, with the goal of moving on to lunar samples in Year 3 or 4. We developed new protocols to test the genotoxicity (mitochondrial and nuclear DNA damage) and cytotoxicity (cell damage) using mouse lung cell and brain cell tissue.

Stony Brook graduate student Donald Hendrix, working with Co-I Hurowitz, has been using electron paramagnetic resonance (EPR) spectroscopy to test hydroxyl radical production from pulverized minerals under different atmospheric conditions (Figure 3). The recent purchase of a frequency counter for our Magnettech MS400 EPR spectrometer will enable the precise identification of radical species formed from mineral powders and slurries, which will be presented at the 2016 NASA Human Research Program Investigators' Workshop (Hendrix et al., 2016). This work expands upon initial EPR measurements by former SBU undergraduate Sarah Port, who found that the act of grinding a mineral (an analog for micrometeorid bombardment that occurs continuously on airless bodies) substantially increases the production of $OH^{\cdot}$ when that mineral comes into contact with a fluid. These results are nearly ready to be submitted to *JGR Planets*, with Port as the first author.

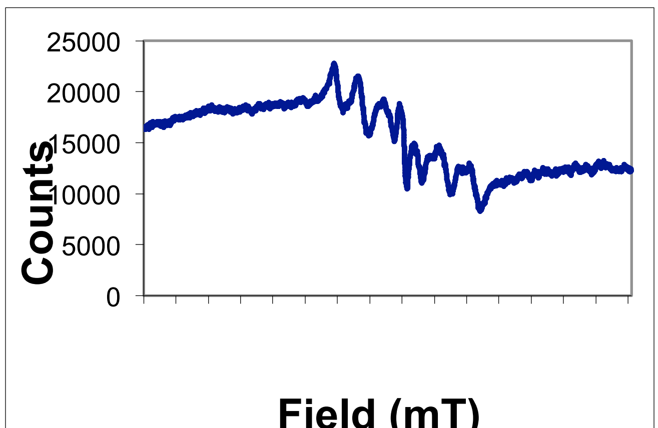


Figure 3. Electron paramagentic resonance (EPR) spectrum of albite, demonstrating presence of unpaired electron species on Al-O-Al linkages.

Former Stony Brook graduate student Jasmeet Kaur (graduated with a Ph.D. in December, 2015), working with Co-I Schoonen, tested the generation of H_2O_2 by several pulverized lunar simulants. There are two major results for this work: (1) the simulants with the highest proportions of glass were the most reactive (as measured by H_2O_2 production), and (2) the reactivity of the simulants decreased with time after being pulverized. This work is currently in review at *Acta Astronautica* (Kaur et al., 2016) and will be presented at the 2016 NASA Human Research Program Guest Investigators' Workshop (Schoonen et al., 2016).

Stony Brook graduate student Rachel Caston has refined assays for genetic damage of cells due to lunar simulant exposure. Most recently, she has successfully isolated DNA from mouse lung slices after treating them with JSC-1A, but she found that she needed to optimize the DNA-protein crosslink assay she is using. This work and related work by Postdoc Jillian Nissen will be presented at the 2016 NASA Human Research Program Guest Investigators' Workshop (Demple et al., 2016).

Theme 4: Maximizing Science from Returned Samples. Our Year 2 work focused on X-ray absorption spectroscopy (XAS) and transmission electron microscope (TEM) analyses of synthetic glasses, amphiboles, meteorites, and lunar samples. A common theme of this work is the use of advanced multivariate analysis to produce robust results that would not otherwise be possible. Dyar et al. (2016a) show how XAS spectra, along with a multivariate model, can determine Fe oxidation state in glasses. Dyar et al. (2016b) show how similar analyses can be used to determine Fe^{3+} in amphiboles. Additional work on the general applicability of multivariate models to spectral unmixing is being conducted by graduate student C. J. Carey (UMass) Co-I's Mahadevan and Dyar and has resulted in two published papers (Carey et al., 2015a,b).

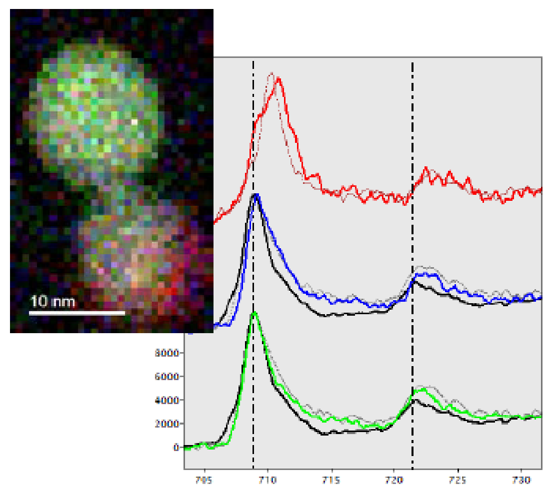


Figure 4. False color RGB image and summed Fe L-edge spectra of two Fe-rich nanoparticles in lunar soil 79221. The bottom rim of the lower nanoparticle (red) is highly oxidized (plotted against Fe^{3+}-bearing basaltic glass), while the core of the lower nanoparticle is metallic Fe (gray). The upper nanoparticle (green) more closely resembles the wustite standard (black) with its narrower peaks.

Postdoc Burgess (Naval Research Laboratory), working with Co-I's Stroud and De Gregorio, has been used synthetic glasses to develop the techniques required to calculate Fe^{2+}/Fe^{3+} ratios using TEM EELS techniques (Burgess et al., 2016a). Additional work by Burgess shows that Fe nanoparticles in space-weathered lunar grains display a variety of oxidation states (Burgess et al., 2016b). Co-I Stroud's recent work has demonstrated the applicability of single-atom TEM analyses for investigating the impurity composition of nanodiamonds in Allende and similar meteorites (Stroud et al., 2016).

Our team has also conducted laboratory analyses of a range of other samples, including X-ray synchrotron analyses of new brachinite-like achondrites (Goodrich et al., 2016), VNIR reflectance measurements of Murchison, electron microprobe analyses of synthetic and lunar plagioclase feldspar (Nekvasil et al., 2015), and mid-IR reflectance and X-ray synchrotron analyses of shocked plagioclase from Lonar Crater, India (Jaret et al., 2015).

2. Inter-team Collaborations

The RIS^{4}E team is dedicated to the concept of inter-team collaboration within the overall structure of SSERVI. Our experiences in Year 2 have provided evidence that the whole of SSERVI is greater than the sum of its parts.

Collaboration with the IMPACT Team: Following the SSERVI site visit to the University of Colorado in October, 2015, PI Glotch and IMPACT PI Mihaly Horani have begun discussions that we believe will lead to a successful collaboration. Glotch and his postdoctoral researcher, Mehmet Yesiltas, will prepare mineral samples, a reflectance standard, and a portable VNIR spectrometer for integration with the CU dust accelerator facility. Our goal is to acquire *in situ* VNIR spectra of samples as they are being continuously bombarded by dust grains in the accelerator. Results from this experiment will be directly compared with samples subjected to laser irradiation experiments meant to simulate micrometeoroid bombardment. We anticipate that this comparison will provide a calibration for the laser wavelength and energy density required to most accurately simulate micrometeoroid bombardment. We are currently in discussions with the IMPACT team to determine the optimal configuration of our samples and spectrometer for the dust accelerator.

Collaboration with the DREAM2 Team: A substantial portion of the RIS^{4}E field investigation was devoted to characterizing the topography of two collapse pits on the Kilauea volcano in Hawaii. These pits are interesting from an exploration perspective because if they extend below the subsurface, they could provide refuge for explorers during solar radiation events. Separately from our field work, DREAM2 Co-I Mike Zimmerman has been modeling the radiation environment and volatile retention capability of lunar pits. RIS^{4}E Co-I's Bleacher and Garry are collaborating with Zimmerman to provide field LiDAR data for pit crater dimensions and to provide geologically realistic constraints on models of volatile retention in the subsurface of airless bodies.

Collaboration with the Italian SSERVI Team: PI Glotch has worked with Dr. Simone Dell'Agnello, Dr. Mariangela Cestelli Guidi and Dr. Antonella Balerna at INFN in Frascati, Italy, to lay the groundwork for future RIS^{4}E analyses at the DAPHNE-Light synchrotron infrared and ultraviolet beamlines. We anticipate that towards the end of Year 3 or the beginning of Year 4, Postdoc Mehmet Yesiltas will travel to Frascati to acquire micro-IR and micro-UV spectra of experimentally space weathered materials that will be generated at Brookhaven National Laboratory in Year 3. We also anticipate that samples subjected to dust bombardment in collaboration with the IMPACT team will be analyzed at DAPHNE-Light.

Other International Collaborations: Dr. Ed Cloutis (University of Winnipeg) is a RIS^{4}E collaborator and a Canadian Lunar Research Network (CLRN) team member, providing a link between the two teams. Dr. Neil Bowles (University of Oxford) is a RIS^{4}E collaborator, providing a link to the UK and broader European Solar System science and exploration communities.

3. Public Engagement

A RIS⁴E journalist conducts an interview in the field

RIS⁴E Journalists: In spring 2015, eight undergraduate and graduate journalism students participated in a semester-long special-topics course offered through Stony Brook University's School of Journalism. During the semester, the students learned about RIS⁴E science and exploration research directly from the RIS⁴E team through classroom visits, interviews, and field trips to RIS⁴E laboratories. The students produced print and multimedia products about RIS⁴E science and scientists. At the conclusion of the course, five students joined the RIS⁴E team during their 2015 field season at the 1974 Kilauea lava flow on the Big Island of Hawaii to document planetary science fieldwork in action. The students observed, photographed, and recorded dozens of hours of video footage from the entire 10-day field campaign. They engaged with astronaut Rick Mastracchio and learned how RIS⁴E research will benefit the next astronauts to explore rocky bodies beyond the Earth. The students posted daily blog updates, shared highlights from the field through social media, and presented their polished work on a public website: http://ReportingRIS4E.com.

All (100%) of the students enjoyed the field excursion to Hawaii and 75% of student respondents said they were more likely to pursue science journalism as a career as a result of their participation in this program. Example statement from a student: "Never stop doing things like this. Bridging science and journalism–two otherwise unrelated fields–is so vitally important for young students to witness...This experience has been nothing short of life-changing. Seeing people who love what they do in action is the best sort of education I can imagine."

Science Communication Workshop: In partnership with the Alan Alda Center for Communicating Science, we invited scientists to participate in an intensive one-day science communication workshop before the 2015 NASA Exploration Science Forum. Twelve scientists participated in a workshop designed to help them improve their skills in communicating about their research with funders, policymakers, the press, the public, and scientists in other fields. The scientists learned to connect with different audiences and to convey the meaning of complex material in vivid, clear language those audiences can understand. Feedback indicated that participants felt the workshop was useful and directly applicable to their work.

Student Fellowships and Outreach: The RIS⁴E team supported 7 undergraduate research fellows during the summer of 2015. Stony Brook graduate students shared RIS⁴E science content in an education program for 5th grade students from disadvantaged school districts on Long Island, and in the first Long Island Maker Festival in Port Jefferson, NY, with over 2,000 local attendees. The RIS⁴E team also highlighted RIS⁴E and SSERVI science and exploration at public engagement events, including International Observe the Moon Night (InOMN) events and GSFC's open house "Explore@NASA Goddard," which drew tens of thousands of attendees. PI Timothy Glotch and InOMN Director and RIS⁴E Education Lead Andrea Jones also offered a virtual training for InOMN hosts. The team regularly shares updates through public presentations (such as a talk on the NASA hyperwall at the 2015 American Geophysical Union Fall Meeting in San Francisco, CA), the RIS^{4}E website, and through RIS^{4}E social media outlets.

4. Student/Early Career Participation

The RIS^{4}E team is committed to training the next generation of Solar System scientists and explorers. In the second year of funding, we have engaged 10 undergraduate students in high level research, fully or partially funded 9 graduate students, who have all contributed substantially to the RIS^{4}E research mission, and fully or partially funded 6 postdoctoral researchers, who are future leaders in NASA's Solar System exploration and research endeavors. Details of undergraduate, graduate, and postdoctoral personnel are listed below.

A. Undergraduate Students

1. Ramyaprabha Bondalapati, Stony Brook University; SBU Pharmacology undergraduate researcher, RIS^{4}E summer intern (2014-present)

2. Sarah Byrne, Mount Holyoke College; RIS^{4}E summer intern (2014, 2015)

3. Christopher Evans, U. S. Naval Academy; RIS^{4}E summer intern (2015)

4. Tristan Catalano, Stony Brook University; RIS^{4}E summer intern (2015)

5. Shaun Mahmood, Kingsborough Community College; RIS^{4}E summer intern (2015)

6. Christian Thomsen, Western Washington University; RIS^{4}E summer intern (2015)

7. Noel Scudder, Stony Brook University; SBU Geology undergraduate researcher; now Ph.D. Geology student at Perdue University (2015)

8. Marco White, University of Vermont; RIS^{4}E summer intern (2014, 2015)

9. Dylan McDougall, Stony Brook University; SBU Geology undergraduate researcher (2015)

10. Katlyn LaFranca, Stony Brook University; SBU Geology undergraduate researcher (2015)

B. Graduate Students

1. C. J. Carey, Computer Science, University of Massachusetts Amherst (2014-present)

2. Rachel Caston, Pharmacological Sciences, Stony Brook University (2014-present)

3. Gen Ito, Geosciences, Stony Brook University (2014-present)

4. Steven Jaret, Geosciences, Stony Brook University (2014-present)

5. Jasmeet Kaur, Geosciences, Stony Brook University (2014-2015; Graduated with Ph.D. in December, 2015)

6. Melinda Rucks, Geosciences, Stony Brook University (2014-present)

7. Katherine Shirley, Geosciences, Stony Brook University (2014-present)

8. Douglas Schaub, Geosciences, Stony Brook University (2015-present)

9. Donald Hendrix, Geosciences, Stony Brook University (2015-present)

C. Postdoctoral Researchers

1. Katherine Burgess, Naval Research Laboratory (2014-present)

2. Jillian Nissen, Pharmacological Sciences, Stony Brook University (2014-present)

3. Elizabeth Sklute, Mount Holyoke College (2014-present)

4. Kelsey Young, Goddard Space Flight Center (2014-present)

5. Mehmet Yesiltas, Stony Brook University (2015)

6. Alexandra Sinclair, Stony Brook University (2014-2015)

Annual Report Format for FINESSE / SSERVI Team, 1 Feb 2016

1. Team Project reports

<u>West Clearwater Impact Structure</u>

The FINESSE team has a cadre of researchers working on unraveling the mysteries of the West Clearwater Impact Structure (WCIS) located in northern Quebec, Canada. Research is focused at Arizona State University (ASU, geochronology) and the University of Western Ontario (UWO, geology and geomorphology). The US science lead for WCIS research is Kip Hodges (ASU) and the Canadian science lead is Gordon Osinski.

Research is focused on five different topics as summarized below.

1. *Isotope geochronology of impactites*. The radiogenic isotope geochemistry of a variety of minerals (as well as impact melt) can be used for determining the age of geologic events, but different chronometers will provide different kinds of information. The most accurate and precise dates for impact rocks are obtained by applying the U/Pb method to zircons that crystallized from an impact melt. However, zircon is an amazingly resilient mineral, and we often find empirically that ancient zircons from target rocks persist through impact events as xenocrysts in impact melts. These xenocrystic zircons often yield U/Pb dates representative of the igneous of metamorphic age of the target rocks, not the impact event. Impact melt products can be dated using the $^{40}Ar/^{39}Ar$ method (a variant of the K/Ar method). Contamination by target rock clasts is often a problem however, but this can sometimes be minimized through the use of laser microprobe techniques. (U-Th)/He dating of xenocrystic or neoblastic zircon (or apatite) can be very useful because the thermally diffusion rates of ^{4}He are relatively high. However, resetting can also occur in association with subsequent hydrothermal activity. We are using multiple geochronology techniques to date the East and West Clearwater impact structures, with age dates to be published in 2016.

2. *Shock metamorphism and complex crater collapse*. This research aims to further our understanding into the mechanism of complex crater collapse. Here, for the first time, 3D shock barometry has been directly compared to the results of numerical models to probe the formation of complex craters (Figure 1). The shock distribution at West Clearwater is consistent with a rheology produced by the block model of acoustic fluidization. Shock pressures are roughly equal across the central uplift at West Clearwater and attenuate faster with depth at greater radial distances. The shock distribution pattern can be explained by a rheology produced by the block model of acoustic fluidization, demonstrating good agreement between the numerical modeling and lab/field observations.

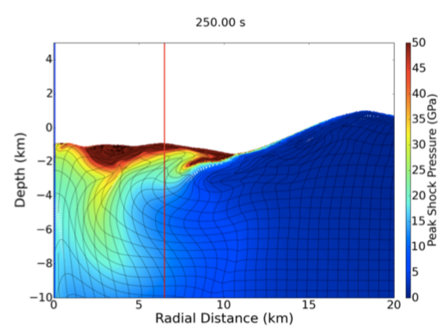


Figure 1. Numerical simulation of WCIS formation showing peak shock pressure as a function of location. Credit: Auriol Rae.

3. *Automated lineament mapping of WCIS*. Impact structures have distinctive lineament patterns, and here we utilize modern satellite and airborne data and image processing techniques to map linear and quasi-linear features associated with the West Clearwater impact structure. A goal is to develop automated methods to constrain the spatial density, distribution, geometric pattern and orientation of extracted features. We record the density, length, orientation, distribution, and geometric pattern (radial vs. concentric) of extracted lineaments. Preliminary findings show the major lineament trend is E-W, which supports observations from manual

lineament mapping on images. This data represents the westward flow of Laurentide glaciation with an age ≈ 8000 – 20,000 years post-impact.

4. *Examining melt veins at WCIS: injected vs in situ melt*. The objective of this research task is to determine the formation processes of melt veins on the central islands of the West Clearwater Impact Structure using petrography and geochemistry. Impact melts can form in two ways: in-situ melting or injected melt. Geochemistry will help to reveal the process forming these melt veins. Similar geochemical composition is likely if melt is produced in situ, and the use of mixing model (which replicates the geochemical signature of a vein using country rock and melt endmembers) is

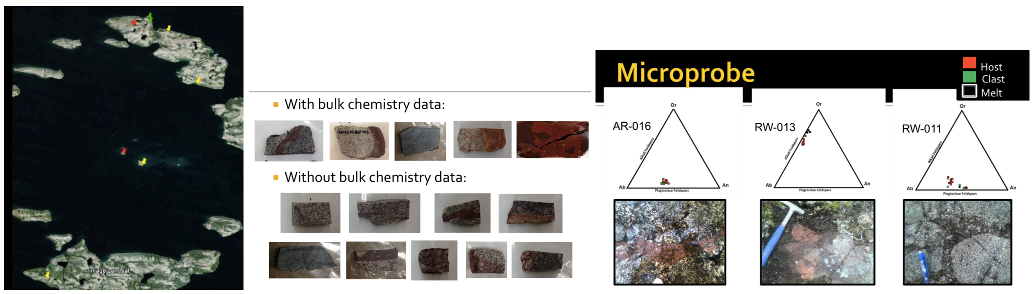


Figure 2. Left. WCIS melt sample locations. Middle: Bulk chemistry (red & green), no bulk chemistry (yellow). Right: Sample AR-016 data shows clasts within the melt vein which plot closely to the host rock. Bulk chemical analysis also shows similar concentrations for all major , minor, and trace elements which is consistent with in situ melting. Data for RW-013 and RW-011 show that the clasts and melt differ more heavily than AR-016 from the host rock, in addition, the vein differs chemically from the host rock in RW-013 bulk chemical analysis, which is consistent with injected melt. Credit: Rebecca Wilks.

used to determine the percent contributions from different lithologies to melt veins. A series of techniques and measurements are used on the returned samples (e.g., petrography, mineralogy, flow textures and shock features, geochemistry, electron dispersive spectroscopy, wavelength dispersive x-ray spectroscopy, bulk chemistry) to determine the origin of the melts (see Figure 2 for example).

5. *Paleomagnetic dating of WCIS*. This research task uses a paleomagnetic dating approach for the East Clearwater impact structure and aims to help answer the question of the impact doublet at Clearwater. We perform rock magnetism measurements to determine the magnetic mineralogy, and determine why only some basements are remagnetized (lithology & location) and how (heating/hydrothermal alteration/shock). Initial results show the same paleomagnetic directions in clasts and groundmass, suggesting the impact melt breccias from the West Clearwater Impact formed at high-temperature. Some basement rocks (granites) inside the crater are remagnetized by the impact. The West Clearwater impact happened during a reverse polarity period at □260-280 Ma. Refinements to the age date and comparisons with other techniques are ongoing.

Craters of the Moon (COTM) National Monument and Preserve

Scientific objectives of the 2016 COTM fieldwork were to collect data that relate to the classification and analysis of COTM lava flows and other volcanic features as planetary analogs. Research included the study of lava flow morphologies, building a database of quantifiable lava flow attributes, sampling for geochemical and petrographic analysis to assess variations related to flow surface morphology, and gathering initial information necessary to guide future field studies. The study of lava flow attributes will lead to the development of synthetic models used in the evaluation of planetary surfaces by remote sensing prior to on-site exploration.

Specific primary objectives for the 2016 field deployment were to acquire 1) Differential GPS (dGPS) profiles on various lava flow surfaces from North Crater, Big Craters, Kings Bowl and Highway flows, 2) UAV (unmanned aerial vehicle) high-resolution imagery from selected regions to produce digital terrain models (DTMs) and georeferenced orthophotographs of lava flow surfaces, 3) LiDAR photography at representative areas, focused on UAV targets and flow margins, 4) In-situ data collection including FTIR scans, ASD visible to near infrared spectra, and XRD scans of selected sites, mostly of sampling locations, and 5) Sample collection for geochemical (XRF) and microscopic (thin-section) analyses.

To achieve these science and data collection objectives, the FINESSE team deployed a suite of field measurement techniques as described below:

1) On-site inspection of volcanic features; including reconnaissance of new targets and close examination of repeat targets; digital imagery, geologic observation, descriptions and interpretations; various field measurements (dimensional, textural, outcrop scale features).

2) Differential GPS of flow surfaces and other volcanic constructs; primarily topographic profiles (~10-20 cm data point spacings); also includes spot locations for various other purposes such as sample collection, marking key field points, etc.

3) LiDAR scans of flow margins, surfaces, other volcanic constructs; variable ranges (~2 – 200m) ties in with dGPS, and hyperspectral imagery and link to remote sensing applications. Figure 3 shows the LiDAR in the field at COTM.

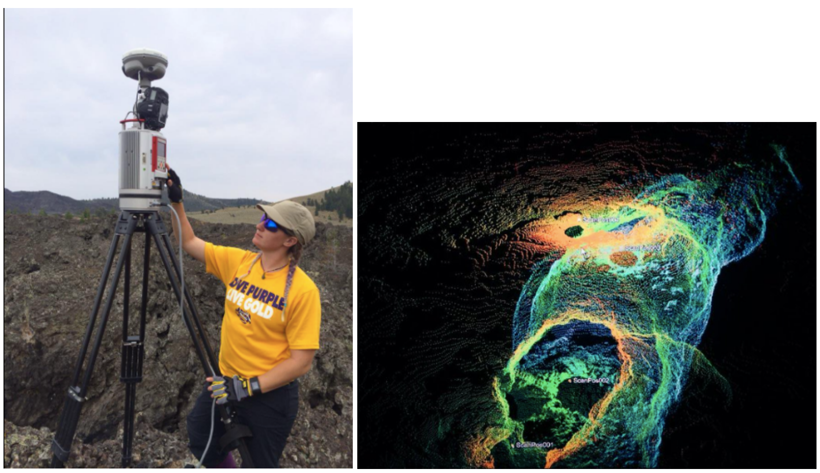


Figure 3. Left: Louisiana State University graduate student Nicole Button operating the LiDAR instrument at COTM 2016. Right: LiDAR scan of lava tube at COTM.

4) In-situ instrument scans; includes FTIR, ASD visible to near infrared spectra, and XRD scans made by portable field devices; important to locate and measure possible changes in mineralogy, chemistry and alteration products of volcanic units. Figures 4 and 5 show an example of field portable NIR spectrometer and XRD system at COTM, respectively.

5) UAV surveys; target regions covered by UAV flights to obtain high-resolution visual imagery and subsequent DTM construction using stereo photogrammetry.

6) Sampling of geologic materials; mainly outcrop sampling of lava flows, but including sampling of tephra, soil.

The scientific richness of the COTM volcanic field site has lead to the development of multiple research projects associated with the FINESSE fieldwork. Here we present a brief overview of several key research tasks.

* Compositional Variations in COTM Lava Flows that Depict Heterogeneity in Eruptive Style and Lava Flow Emplacement. This research incorporates the field data (discussed above)

combined with computer modeling of compositional variability as a function of lava flow morphology.

Figure 4. Idaho State University graduate student Hester Mallonee using a field portable infrared spectrometer at COTM 2016.

* Classification of Lava Flow Types in a Polygenetic Lava Field. The richness in diversity of lava flow types at COTM offers a unique opportunity to assess various parameters for lava flow identification and ground truthing at COTM. These results can then be extrapolated to understand lava flows on other planetary bodies. This work includes remote sensing data analysis, surface topography and radar data, and ground truthing with field portable instrumentation (FTIR, ASD, XRF, etc.) combined with the integration of the visible, NIR, shortwave and thermal IR remote sensing data in a georeferenced framework.

* Mathematical Model of Lava Flow Geomorphology Based on Digital Topography. This research focused on the quantification of lava flow surfaces (field measurements from UAV DTMs, dGPS) combined with a characterization of surface roughness.

* Investigation of Lunar Analog Volcanic Features by High-Resolution Digital Topography and Imagery. This work focuses on the Inferno Chasm region with multiple geomorphic analogs to lunar features have been measured and quantified in detail in combination with models of formation.

* Assessment of Ejecta Size and Distribution Around the Kings Bowl Explosion Crater. Rock size distributions have been measured in the field and compared with numerical models of phreatic ejection from the King's Bowl structure to constrain the amounts of volatile interaction with subsurface magma as well as the timing and number of explosions to create the current King's Bowl landscape.

* Volcanology of the Kings Bowl fissure system and lava field as a planetary analog for dike emplacement, pit crater chains and explosive fissure eruptions. Quantitative assessments of these multiple volcanic features as lunar analogs have been conducted in combination with models of formation applicable to other planetary surface and subsurface geology.

* Development of Induced TL (Thermoluminescence) Age Dating at COTM. TL age dating is being used on COTM samples to constrain the history of volcanic activity and assist with reconstruction of the volcanic history of the region.

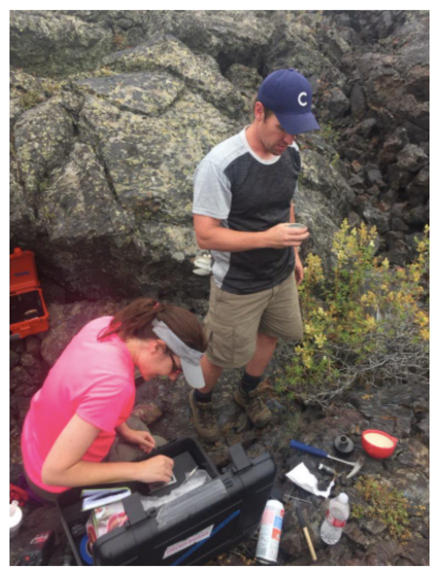


Figure 5. Running volcanic samples through the field portable XRD instrument at COTM 2016.

2. Inter-team Collaborations

FINESSE is committed to inter-team collaborations which strengthen the science and exploration portfolios of each party. To that end, FINESSE has a very welcoming collaboration policy in that we encourage cross-team collaboration with team members or collaborators from any other SSERVI teams and hold no restrictions against collaboration at any time. We foster a spirit of cooperation for the advancement of science and exploration.

Here we share multiple examples of inter-team collaborations. Collaboration with the VORTICES team (A. Rivkin PI, APL) has resulted in a new research project being conducted regarding planetary volcanology. VORTICES Co-I Dr. Alexandra Matiella-Novak joined the FINESSE team for two weeks during the 2016 deployment to Craters of the Moon National Monument and Preserve. Through this experience, Matiella-Novak is now leading a research project to study impact features present in the King's Bowl lava field in Idaho. The King's Bowl feature was caused by the ejection of blocks during the phreatic eruption that formed the Kings Bowl pit, and the ejected blocks subsequently impact into a partially solidified lava pond. Work is ongoing now to compare and contrast these features with analogous self- secondary impact features, such as irregular, rimless secondary craters ("splash craters"), observed in lunar impact melt flows in an effort to better understand these unusual features, capitalizing on the Idaho field measurements and Lunar Reconnaissance Orbiter Narrow Angle Camera (LRO NAC) for lunar splash craters. Matiella-Novak is presenting this work at the upcoming 2016 Lunar and Planetary Science Conference, with authors from VORTICES, FINESSE, and our international partner in Canada.

In 2016 the FINESSE team led an exploration-focused presentation that included collaboration with the RISE team. FINESSE Co-I Dr. Barbara Cohen led the publication of a paper in the *Journal of Human Performance in Extreme Environments* focused on pre-mission requirements and training for astronauts to enable successful scientific sample collection. This research was conducted at WCIS during the 2015 FINESSE deployment. FINESSE welcomed RISE Co-I Kelsey Young on this expedition, and Young is a coauthor on this publication.

Cohen, Barbara A.; Lim, Darlene S. S.; Young, Kelsey E.; Brunner, Anna; Elphic, Richard C.; Horne, Audrey; Kerrigan, Mary C.; Osinski, Gordon O.; Skok, John R.; Squyres, Steven W.; Saint-Jacques, David; and Heldmann, Jennifer L. (2015) "Pre-Mission Input Requirements to Enable Successful Sample Collection by a Remote Field/EVA Team," *Journal of Human Performance in Extreme Environments*: Vol. 12: Iss. 1, Article 7, dx.doi.org/10.7771/2327-2937.1071.

FINESSE also has close collaborations with the SSERVI Canadian Lunar Research Network (CLRN). Dr. Gordon Osinski is the Lead for CLRN, and is a key FINESSE Collaborator. Osinski is the Canadian lead for the FINESSE Impact Science at WCIS, and collaborates with the FINESSE team to conduct SSERVI science and exploration research. CLRN supports multiple researchers, post-docs, and graduate students working on WCIS research. Of note is Dr. Catherine Neish who recently joined the CLRN team at the University of Western Ontario. Dr. Neish is a member of the FINESSE team and has conducted fieldwork at Craters of the Moon on FINESSE expeditions. She is leading the radar studies in Idaho as an analog for similar radar signatures observed on the Moon. She leads the radar studies of volcanics for FINESSE, and also advises a new FINESSE collaborator Dr. Michael Zanettti as her new post-doctoral researcher.

FINESSE also collaborates with the KARI Lunar Exploration Program. Dr. Kyeong Kim of KIGAM (Korea Institute of Geosciences and Mineral Resources) is a FINESSE Collaborator. Dr. Kim has conducted fieldwork at Craters of the Moon in Idaho and is currently processing returned samples for compositional variations using her XRF facilities in Korea. She is contributing to the science program of FINESSE, and also collaborating on Education and Communication activities with FINESSE. Dr. Kim is using content from her FINESSE collaborations for her classes where she serves as a professor at the University of Science and Technology in Korea. She is also developing content based on FINESSE research for the Creative Geo EduCamp for Students and Teachers to teach about planetary science to students and teachers in Korea.

3. Public Engagement (including EPO) Report

Figure 6. The FINESSE field team at Craters of the Moon.

FINESSE Spaceward Bound. The FINESSE Spaceward Bound program engages teachers in authentic science research experiences on field excursions with NASA scientists (Figure 6). Through a partnership with the Idaho Space Grant Consortium, we bring students and teachers into the field to conduct science and exploration research in Craters of the Moon National Monument and Preserve (COTM) in Idaho with the FINESSE science team. During the summer of 2015, five K–12 teachers and a high school student participated in the FINESSE Spaceward Bound program, alongside 31 FINESSE scientists. The participants were engaged in all aspects of the FINESSE field campaign: they rotated through field sub teams, hiked with them through lava flows, operated field instruments, collected data, and participated in science discussions. They also participated in FINESSE Media Day, which the team has supported each field season at COTM. Once teachers return to the classroom, they share their experiences and enhanced science content/process knowledge with their students and continue to deepen their understanding of FINESSE/NASA planetary science research and exploration with support from educational activities, resources, and opportunities we provide or recommend, and sustained contact with the FINESSE team.

Feedback from both the scientists and the teachers who participated in this program was overwhelmingly positive. Example comments from the science team include: “It was awesome”; “The teachers were phenomenal”; “All five teachers were excellent: energetic, interested, and helpful. They became integrated in the team.” Every teacher who participated in the 2015 program wants to return. Example teacher comments include: “Watching active scientific process has been exhilarating…my association with Spaceward Bound has helped to transform my classroom into a haven for STEM education.” As a result of participation in this program, one educator developed curriculum and programming to be used in informal science education impacting over 20,000 elementary students, teachers, families, college students, and community members throughout Northern Idaho and Eastern Washington. We presented an overview of the program at the 2015 American Geophysical Union (AGU) Fall Meeting in San Francisco, CA and will present our evaluation results at the Lunar and Planetary Science Conference in Houston, TX in March 2016. Teachers are included as co-authors on this scientific publication.

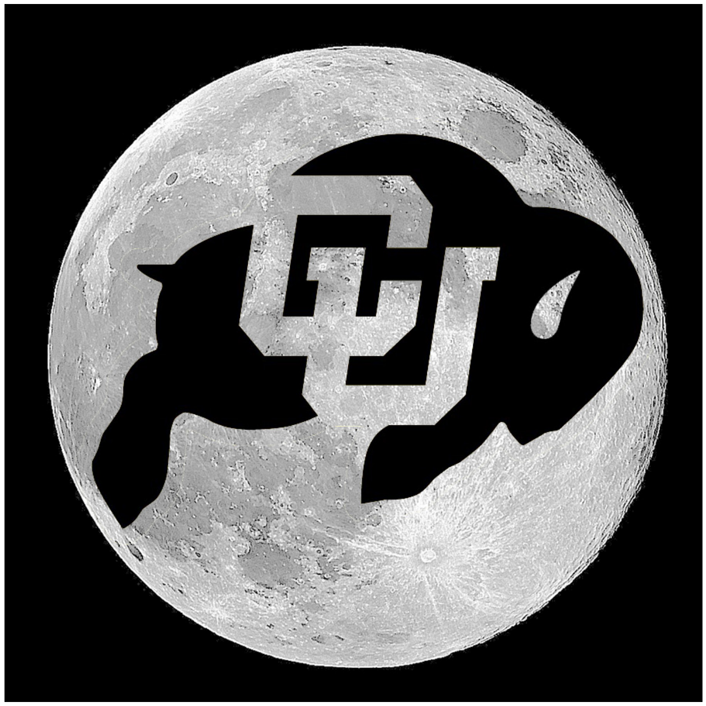
Team Outreach. The FINESSE team is committed to publicly sharing our research and interest in planetary science and exploration. We support a SSERVI Seminar Speaker Series, through which we highlight FINESSE and SSERVI science and exploration highlights for the NASA Museum Alliance and NASA Solar System Ambassadors, who in turn share this content with their audiences in venues around the country and the world. The team presented FINESSE research through public presentations, including a talk on the NASA Hyperwall at AGU, and through media outlets, such as a guest blog on The Planetary Society website, the AGU Eos magazine, and the FINESSE website and social media accounts. A FINESSE collaborator also highlighted FINESSE research in a teacher workshop in Korea. Outreach events the FINESSE team supported in 2015 include International Observe the Moon Night and Explore@NASA Goddard, which each drew tens of thousands of participants.

4. Student/Early Career Participation

1. Chris Borg, Idaho State University, undergraduate, science research focused on King's Bowl phreataic crater and reconstruction of blast pits based on modeling and field data
2. Sean Purcell, Idaho State University, graduate student, science research based on geochemistry of lava flow features in Idaho and implications for lava emplacement and evolution
3. Hester Mallonee, Idaho State University, graduate student, analysis of surface topography of volcanic flows and relation to flow emplacement and history
4. Christopher Haberle, Arizona State University, graduate student, doctoral dissertation focused on remote sensing (vis-nir) and ground truth data of Craters of the Moon National Monument and Preserve
5. Ethan Schaefer, Arizona State University, graduate student, fractal planform geometry of lava flow margins and its link to the roughness of lava flow surfaces
6. Anna Brunner, Arizona State University, graduate student, doctoral dissertation based on geochronology analysis of West Clearwater Impact Structure
7. Audrey Horne, Arizona State University, graduate student, doctoral dissertation based on geochronology analysis of West Clearwater Impact Structure
8. Nikhil Vadhavkar, MIT, graduate student, research pertaining to UAS/UAV design and deployment for planetary missions
9. Taylor Judice, Louisiana State University, undergraduate, research regarding the geomorphology and geochemistry of terrestrial and planetary lava flows
10. David Susko, Louisiana State University, undergraduate, research regarding the geomorphology and geochemistry of terrestrial and planetary lava flows
11. Nicole Button, graduate student, Louisiana State University, research regarding robotic field operations, geology and geochemistry of lava flows
12. Duncan Crowley, MIT, graduate student, hyperspectral imaging and mineral identification of volcanic deposits
13. Michael Zanetti, University of Western Ontario, post-doctoral researcher, radar studies and comparisons between terrestrial lava flows in Idaho and lunar flows
14. Alexander Sehlke, NASA Ames Research Center, post-doctoral researcher, rheological evolution of planetary basalts during cooling and crystallization & effects of geochemistry and geomorphology
15. Deepak Dhingra, University of Idaho, post-doctoral researcher, geology and geochemistry of terrestrial lava flows for comparative planetology (note: graduate student from Brown University / SEEED).
16. Auriol Rae, Imperial College London, post-doctoral researcher, shock metamorphism and complex crater collapse (West Clearwater Impact Structure)
17. Rebecca Wilks, University of Western Ontario, graduate student, analysis of melt veins at West Clearwater Impact Structure with implications for identification of injected vs in situ features
18. William Zylberman, University of Western Ontario, graduate student, paleomagnetic dating of West Clearwater Impact Structure
19. Mary Kerrigan, University of Western Ontario, graduate student, impact generated hydrothermal activity at West Clearwater Impact Structure
20. USIP (Undergraduate Student Instrument Project) student team, undergraduate team, FINESSE supported the USIP proposal titled TATER TOTS (*Training in Advanced Technology and Exploration Research To Optimize Teamwork in Space)* submitted by the University of Idaho to fly UAS vehicles and collect aerial data (high resolution spectral data and thermal imaging) for use in FINESSE research program. FINESSE providing technical oversight and mentorship to the student team in collaboration with the Idaho Space Grant Consortium.

January 30, 2016

NASA SSERVI
Institute for Modeling Plasmas, Atmospheres, and Cosmic Dust (IMPACT)



Year 2 Report

Period of Performance: 01/01/2015 - 12/31/2015

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Summary

IMPACT remains dedicated to studying the effects of hypervelocity dust impacts into refractory, icy, and gaseous targets; to building new laboratory experiments to address the effects of UV radiation and plasma exposure of the surfaces of airless planetary objects; to developing new instrumentation for future missions to make in situ dust and dusty plasma measurements in space; and to providing theoretical and computer simulation support for the analysis and interpretation of laboratory and space-based observations. IMPACT provides access to its facilities to the space physics community and supports a large number of undergraduate and graduate students.

1. Project Reports

1.1 Accelerator Projects

Accelerator Performance: The accelerator is a source of hypervelocity dust particles with radii in the range of 10 nm < a < 5 µm (Fe), and speed range in excess of 100 km/s (Figure 1). We have successfully accelerated particles with a variety of composition, including Fe, Ag, olivine, and latex. Our latest speed record is 117 km/s for a 20 nm radius Fe particle. The performance of the accelerator remains critical for the ongoing testing and follow up calibrations of the engineering model of the Lunar Dust Experiment (LDEX) for the LADEE mission.

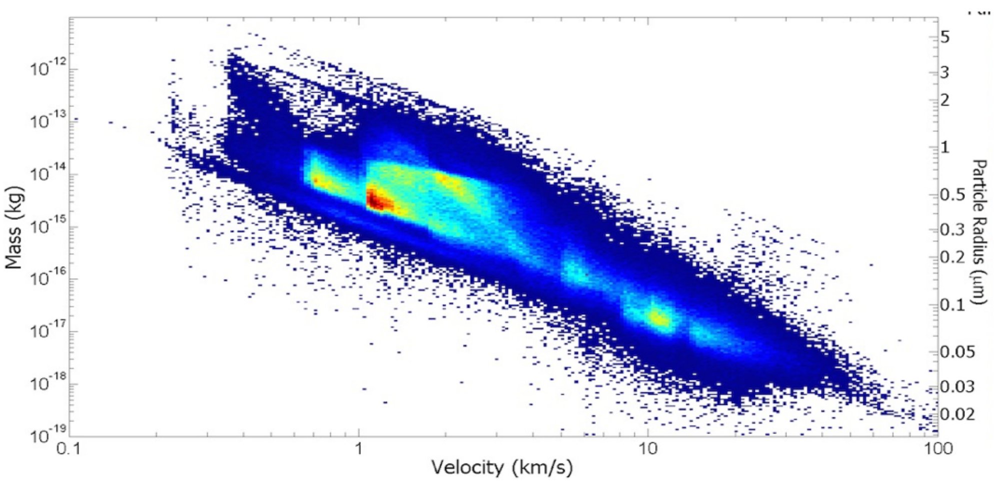


Figure 1. The performance of the IMPACT dust accelerator, showing the mass and speed distribution of the accelerated *Fe* particles.

The Development of Ice and Gas Targets: We have completed two major target upgrades: a cryogenic ice target and a high-pressure gas target. Cryogenic targets enable the studies of the effects of dust bombardment on ices throughout the solar system, including the permanently shadowed regions of the Moon, or the icy surfaces of outer solar system objects. The gas target chamber is used to understand the ablation of meteoroids in planetary atmospheres, or in the case of the Earth, to improve our ability to analyze and interpret the data from ground-based meteor-radars.

Ice Target Impact Experiments: The ice target consists of a LN_2 cryogenic system connected to both a water-ice deposition system as well as a movable freezer/holder for a premixed liquid cartridge. We have begun an experimental campaign into the bombardment of a variety of frozen targets and simulated ice/regolith mixtures, and the assessment of all impact products (solid ejecta, gas, plasma) as well as spectroscopy of both the impact-produced light flashes and the reflected spectra (UV, visible, IR). Figure 2 shows example initial measurements of cluster size distributions generated in dust impacts of pure water ice (Nelson et al., 2015).

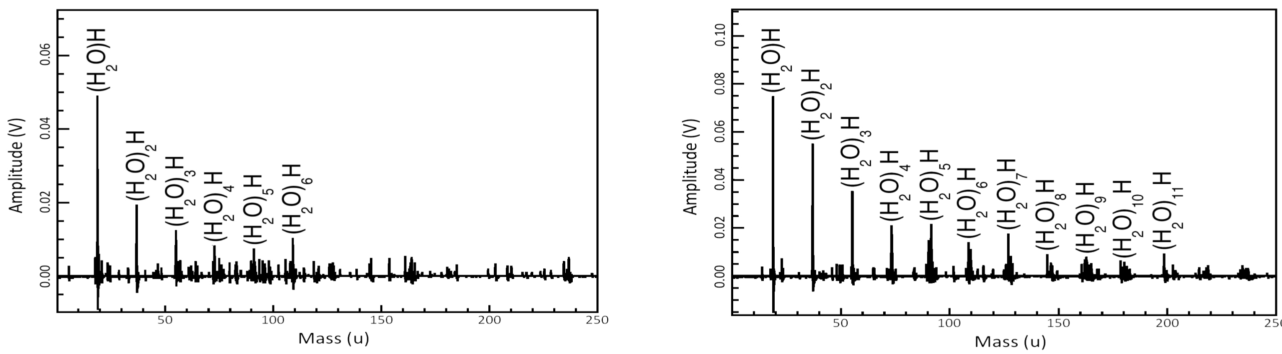


Figure 2. Initial results of the distribution of water clusters using a Time-of-Flight (TOF) mass spectrometer from *Fe* particle impacts with speed of 6 (left) and 20 (right) km/s into pure water ice.

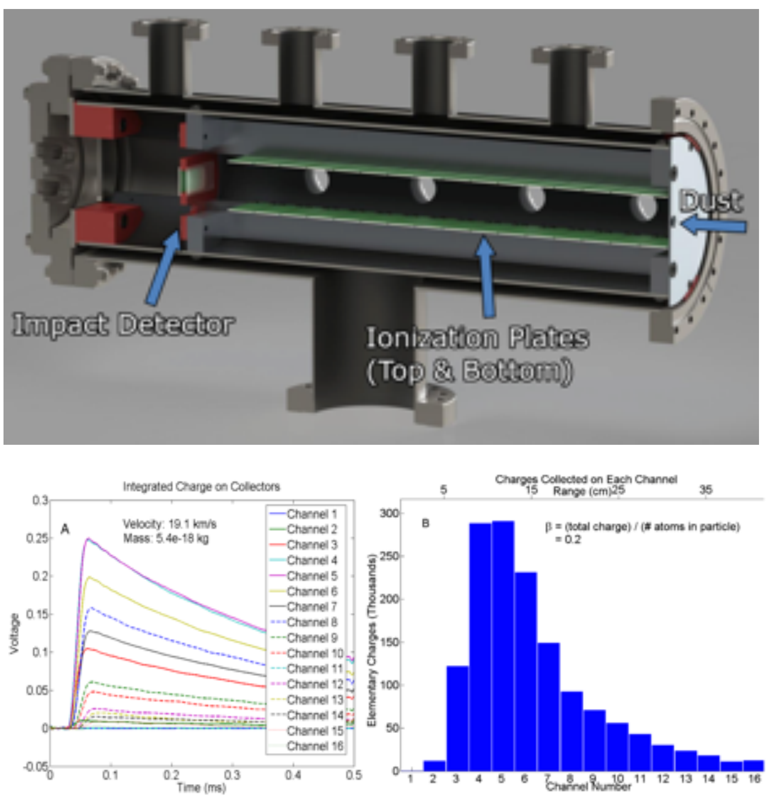


Figure 3. A cutaway diagram of the gas target chamber containing the ionization plates and the impact detector (top). The charge collected in each channel as function of time (bottom left), and the integrated total charges (right).

Gas Target Impact Experiments: The amount of cosmic dust reaching our atmosphere remains poorly constrained, and it is currently estimated in the range of 50 - 150 tons/day. The largest uncertainty using ground-based radar observation is the ionization efficiency (β) of a micrometeoroid particle to generate a plasma trail, and for using optical telescopes is their luminous efficiency. The gas-target experiments address these to enable improved mass estimates of micrometeoroids from these measurements. The gas target consists of a differentially pumped chamber kept at moderate background pressures, such that high-velocity (≥10 km/s) micrometeoroids are completely ablated within 10's of cm (i.e. within the measurement chamber). The chamber is configured with segmented electrodes to perform a spatially resolved measurement of charge production during ablation (Figure 3), and localized light-collection optics enable an assessment of the light production (luminous efficiency). In a recent study, micron and sub-micron sized iron particles were accelerated to meteoric velocities (20-50 km/s), and introduced into our gas chamber filled with N_2, air, CO_2, and He gases pressurized to 0.1-0.5 Torr. For these conditions the iron dust particles undergo complete ablation over a short distance. The ions and electrons of the generated plasma trail are collected on biased electrodes, and β is calculated from the total collected charge and the initial mass of the particle (Thomas et al., 2015).

1.2 Small-scale Laboratory Experiments

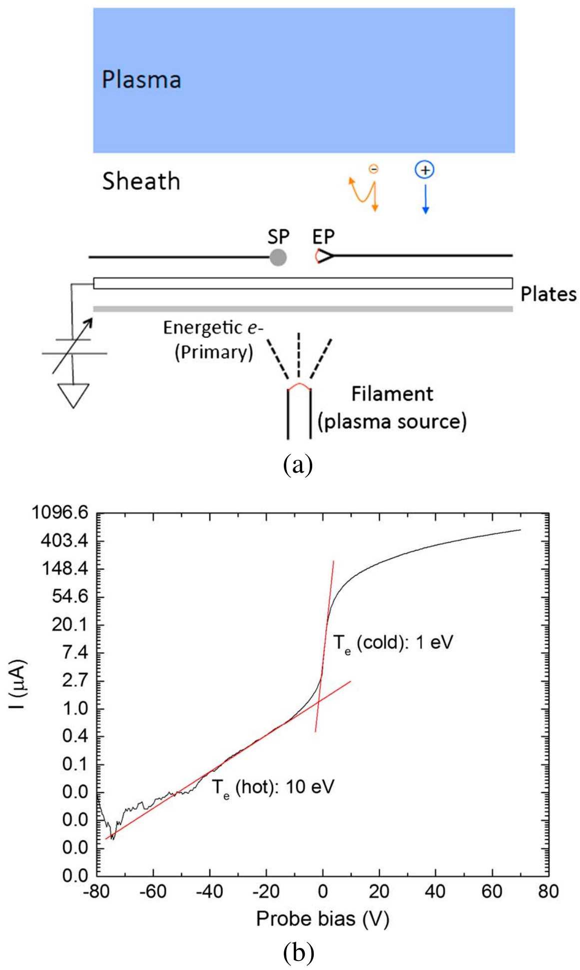


Figure 4. (a) Schematic of the setup for thermal plasma experiments. SP: spherical probe. EP: emissive probe. (b) A semilogarithm plot of an I-V curve measured in the bulk plasma. Two electron populations are shown: cold and hot with temperatures 1 eV and 10 eV. The densities of the hot and cold electrons are 3% and 97%, respectively.

Laboratory efforts focused on a) optimizing the data interpretation of in situ plasma diagnostic tools, especially Langmuir Probes (LP) by recognizing and modeling the effects of the plasma sheaths surrounding a spacecraft; and b) the charging, mobilization and transport of dust on the surfaces of airless planetary bodies.

Langmuir Probe Experiments:

LP on spacecraft have been used for characterizing the ambient plasma parameters in space. When their boom is short compared to the Debye length, the probes remain immersed in the spacecraft sheath, corrupting the measurement by causing the current-voltage (I-V) characteristics to deviate from that of a probe far away from the spacecraft. We can now recognize when a Langmuir probe is in a sheath, based on the secondary electron (SE) emission from the probe itself. The I-V characteristics of a spherical probe were investigated in a plasma sheath above a conducting plate. Plasmas with cold and hot electrons (1 eV and 10 eV), as well as mono-energetic electrons (50–100 eV), were created. The derivative (dI/dV) of the probe I-V curves shows that in addition to a “knee” at a potential more positive than the plasma potential, an additional knee appears at a sheath potential at the probe location. This additional knee is created due to the SE emission from the probe and is identified as an indication of the probe being immersed in the sheath (Wang et al., 2015).

Dust Transport Experiments:

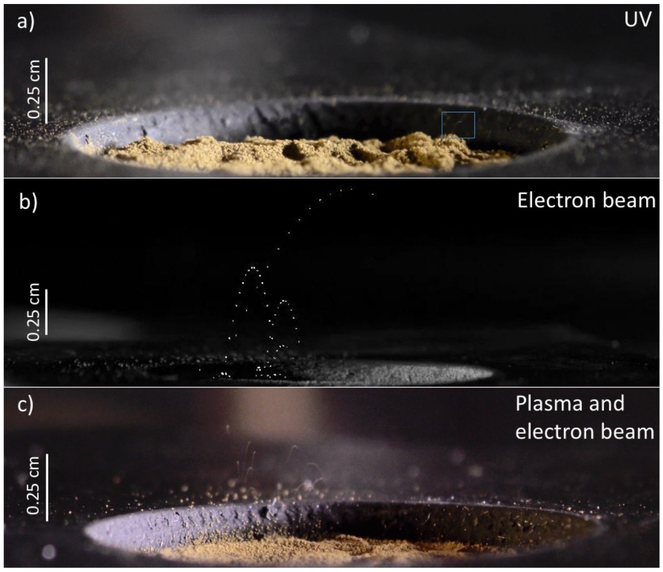


Figure 5. Images of dust transport and lofting trajectories in a) UV, b) electron beam, and c) plasma and electron beam experiments. Dust particles were loaded in a crater 1.9 cm in diameter and 1 mm in depth on a graphite surface. Mars simulants (38-48 µm in diameter) were used in the experiments because their irregular shapes and mass density (1.9 g/cm^{-3}) generally resemble the regolith particles of most airless planetary bodies in the inner solar system. A blue square in a) indicates a lofting trajectory captured under UV illumination. Deposition of dust particles on the surface outside the crater also indicates their hopping motions (Wang et al., in preparation, 2016).

Electrostatic dust transport was first suggested five decades ago to explain the images of the Surveyor 5, 6 and 7 missions of the lunar horizon glow, a bright hovering cloud observed shortly after sunset on the Moon. High altitude lunar streamers reported by the Apollo astronauts, the intermittently appearing radial spoke features first seen by the Voyagers over the rings of Saturn, and the accumulation of fine dust in ponds on the surface of Asteroid 433 Eros by the NEAR-Shoemaker mission, are all examples of dust transport across vast regions without winds or flowing water. However, in all these examples, the combination of dust charges and electric fields estimated from surface - plasma interaction models cannot explain dust mobilization. Our experimental results show that the interaction of a dusty surface with UV radiation or plasmas is a volume effect. The emission and re-absorption of photo and/or secondary electrons from the walls of micro-cavities formed between insulating dust particles below the surface are responsible for generating unexpectedly large charges and intense electric fields.

Dust particles with radii < 44 µm jumping to several cm heights with initial speeds ~ 0.5 m/s were observed in the laboratory. Coulomb repulsion between like charges, and the additional acceleration due to surface electric fields are the sources of their initial kinetic energy. We expect this process to be efficient on all airless planetary regolith surfaces to redistribute fine dust particles, and usher them into depressions. We suggest that space missions carrying an intense UV or electron source could return surface dust samples without physical contacts.

1.3 Theory Support

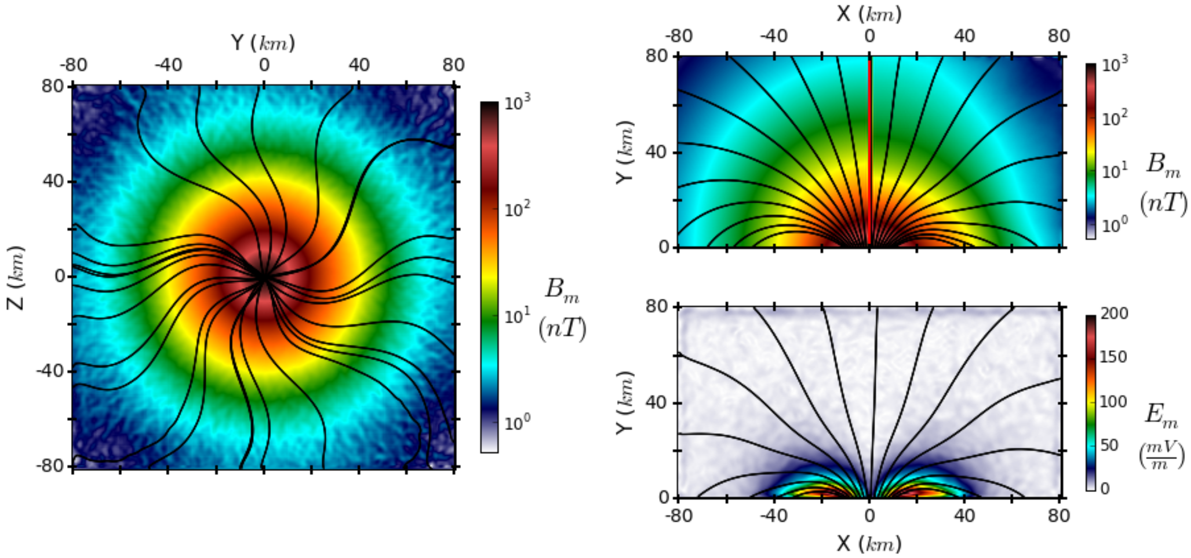


Figure 6. Two-dimensional profiles of the magnetic and electric field configurations above a lunar magnetic anomaly. Superimposed in black are projected magnetic field lines. Left: the magnetic field magnitude in the YZ plane at x = 1km above the lunar surface. Upper right: Initial (left of the red marker) and final, compressed configuration (right of the red marker) of the magnetic field magnitude in the XY plane through the dipole center. Lower right: The electric field magnitude in the XY plane through the center of the diploe (Deca et al., 2015).

A detailed notion of the solar wind synergy with lunar magnetic anomalies (LMAs) is vital both to identify its implications for lunar exploration and to enhance our physical understanding of the particle dynamics in partially magnetized plasmas. We reported on the first three-dimensional full-kinetic and electromagnetic particle-in-cell simulations of the solar wind interaction with a vertical dipole centered just below a perfectly absorbing surface, resembling a medium-size LMA embedded in the lunar regolith, under plasma conditions such that only the electron population is magnetized (Figure 6). This condition has also been implemented in many of our laboratory experiments. We focused on the general structure of the resulting electromagnetic fields to discuss the ion and electron dynamics determining the interaction by means of the energy and velocity distribution functions. More than three decades after their initial discovery by the Apollo missions, LMAs continue to be an intriguing phenomenon to interpret possible correlations with lunar swirls, high albedo markings and space weathering on airless bodies in our solar system. This work delivers the next piece of the puzzle to fully comprehend and interpret the observations (Deca et al., 2015).

2. Inter-team Collaborations

DREAM-2 and IMPACT

We continued our collaborations with Andrew Poppe and Jasper Halekas on the analysis and interpretation of LADEE/LDEX and ARTEMIS measurements. We are pursuing close collaborations on plasma simulations of magnetic anomalies and the comparisons of these with both laboratory experiments and space observations.

CLASS and IMPACT

CLASS PI, Prof. D. Britt (U. Central Florida) gave a LASP seminar in 2015, and continued our collaboration to discuss micrometeoroid bombardment experiments which address the physical properties of icy-regolith surfaces.

ISET and IMPACT

We collaborated with D. Nesvorny on the interpretation of LDEX measurements providing a new test case for evaluating model predictions of the various interplanetary dust sources bombarding the Earth/Moon system.

SEEED and IMPACT

SEEED PI, Prof. C. Pieters and M. Horanyi participated in the CLASS/SEEED seminar series on the Martian moons Phobos and Deimos, discussing their surface properties, and the physical and chemical processes shaping them.

International Partners

We continued our close collaborations with our international partners at the University of Stuttgart (Prof. R. Srama, PI) and the University of Leuven, Belgium (Prof. G. Lapenta).

3. EPO Highlights

3.1 International Observe the Moon Night (IOMN)

A small crowd is gathering on the night of 9/18/2015 to look at the Moon. The attendance was boosted by the Boulder Beer Festival next door..

Saturday, September 18, 2015, marked the fifth annual International Observe the Moon Night). InOMN is worldwide outreach event to get the public interested in the Moon, and give them a chance to look through telescopes. For the fifth time, IMPACT students and staff participated in InOMN and set up two homemade reflecting telescopes with 15” and 17” primary mirrors. The telescopes, built by CU physics Professor Emeritus Scott Robertson, were set up at the Courthouse Lawn on the Pearl Street Mall in downtown Boulder. At least 200 people stopped by and “oohed” and “aahed” as they peered through the eyepieces; for most it was their first time looking at the Moon through a telescope.

3.2 Teacher Professional Development

A teacher's observations of the moon, using her iPhone camera and the 16" telescope at CU’s Sommers-Bausch Observatory.

We have hosted one weeklong teacher professional development program for 27 middle and high school teachers in June of 2015. Working with the Cooperative Institute for Research in Environmental Sciences (CIRES) educational office and the Lunar and Planetary Institute, we provided content on the Sun and solar system, planetary exploration, small bodies and moons, and in the final day of the workshop, teachers created their own lesson plans incorporating these ideas. A portion of the week focused on planetary and lunar formation, and specifically how we gather evidence to support formation models. A researcher, Julien Salmon from SwRI, gave a fascinating lecture on lunar formation and modeling. Teachers took field trips to the observatory to view the moon and make observations, as well as the planetarium to solidify some of the concepts covered during the week. NASA missions focused on included SDO, Mars missions throughout time, MESSENGER, LRO, and New Horizons. We included LASP- and NASA-developed hands-on educational materials, including the LASP engineering program “Project Spectra!”, and materials from SDO, LRO, and other NASAWavelength materials.

4. List of undergrad students, grad students, postdocs, and new faculty

Graduate Students	Project
1) Edwin Bernardoni	Plasma theory
2) Jamey Szalay	LDEX Theory support (graduated 2015)
3) Leela O'Brien	Detector design and fabrication
4) Evan Thomas	Micrometeoroid ablation phenomena
5) Rudy Namiskis	Dust instrument data analysis (graduated 2015)
6) Marcus Piquette	Surface/plasma interaction modeling
7) JR Rocha	Instrument development
8) Ben Southwood	Dust dynamics modeling
9) Michelle Villeneuve	Instrument development
10) Zach Ulibarri	Ice target experiments
11) Lihsia Yeo	Solar wind experiments
12) Michael DeLuca	Micrometeoroid ablation experiments
13) Joseph Samaniego	Langmuir probe measurements
Summer Graduate Interns	
14) Sam Alperin	Dust charging simulations
Undergraduate Students	
15) Forrest Barnes	Control software development
16) John Fontanese	Small accelerator experiments
17) William Goode	Accelerator diagnostic design
18) Andrew (Oak) Nelson	Ice target development
19) Andrew Seracuse	Beam detector development
20) Joseph Schwan	Dust dynamics in plasma
21) Robert Beadles	Langmuir probes in sheath
22) Juliet Pilewskie	Dust dynamics modeling
23) Michael Gerard	Lunar swirls modeling
24) Alexandra Okeson	Dust instrument software development
25) Jared Stanley	LDEX modeling support
26) Ethan Williams	Instrument development
27) Eric Junkins	Instrument development
28) Jia Han	Solar wind experiments
29) Zuni Levin	SIMION studies
30) Ted Thayer	Antenna signals from dust impacts
31) Elizabeth Bernhardt	Accelerator experiments
32) Max Weiner	Mass-spectra
High School Students	
33) Dolfin Olsen	Mechanical design of motorized translation table
Postdocs	
34) Jan Deca	Computer simulations of plasma - surface interactions
Retired Volunteer Scientist	
35) Dr. Richard Dee	Cryogenic target development

Annual Report – Year 2 **PI David A. Kring**

1. Team Project Science, Exploration, & Related Training Activities

Our team is in the second year of an intensive investigation of (i) the consequences of near-Earth object (NEO) impacts in the Earth-Moon system, (ii) the sources of those impactors as a function of time, (iii) implications those sources have for the past evolution of the Solar System, and (iv) implications those results have for the hazards of future impacts on Earth. Those scientific objectives are augmented with (v) human-assisted lunar sample return mission concept studies that involve the Orion vehicle, (vi) radar observations of potential human exploration asteroid targets, and (vii) analyses of meteoritic samples of near-Earth asteroids that have properties relevant to potential human exploration asteroid targets (e.g., via the Asteroid Retrieval Mission). We involved high school, undergraduate, and graduate students in those science and exploration research studies. We also developed a new field training and research program for graduate students in the Zuni-Bandera Volcanic Field. We continued to train postdoctoral researchers and began to develop the geologic curriculum for the 2017 class of astronauts. An astronaut that we had previously trained captured an image from the ISS that was used in the Zuni-Bandera field training program.

CLSE used computer hydrocodes to simulate large, basin-size impact events on the early Earth and Moon (Fig. 1). Those simulations show that impact processes and resulting sizes of basins are a strong function of target temperature. Thus, impact events on a hot early Earth or Moon produced different outcomes than geologically younger events. We compiled an immense array of simulations to extract analytical relationships among the governing parameters. We published those relationships (Potter et al., 2015), which will allow investigators throughout the community to quickly calculate the outcome of an impact event without the burden of running a lengthy and expensive hydrocode simulation.

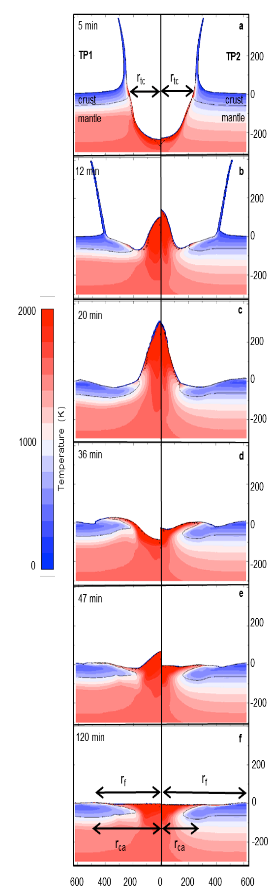


Fig. 1. The basin-forming process for two impacts into targets with different temperature profiles.

We continued to develop new siderophile element and isotopic techniques for identifying the types of impactors that produced early Solar System impact craters. By developing a strategy of *isotope genetic testing*, we are taking advantage of distinct nucleosynthetic contributions to planetesimals that accreted over 4.5 billion years ago. Those diverse nucleosynthetic contributions, or stellar ingredients, were incorporated into our Solar System after being shed by exploding stars that showered the interstellar medium with debris. In particular, our team is analyzing s-process Mo and Ru isotopes (Fig. 2) with increasing analytical precision. The work (Bermingham et al., in press) already suggests that material associated with enstatite chondrites may not have been a significant late component to the Earth-Moon system.

That early accretion also delivered volatile and moderately volatile elements. We continued to analyze the distribution of OH in lunar samples and began to develop a new technique to analyze moderately volatile elements in lunar samples (Neal and Burney, in press). Those types of Year 2 analyses will be evaluated with experimentally derived partition coefficients in Year 3. Preliminary results suggest volatiles (including O and H) are heterogeneously distributed. Suites of lunar materials that sampled the lunar interior at different depths at different times in the Moon's evolution are underway.

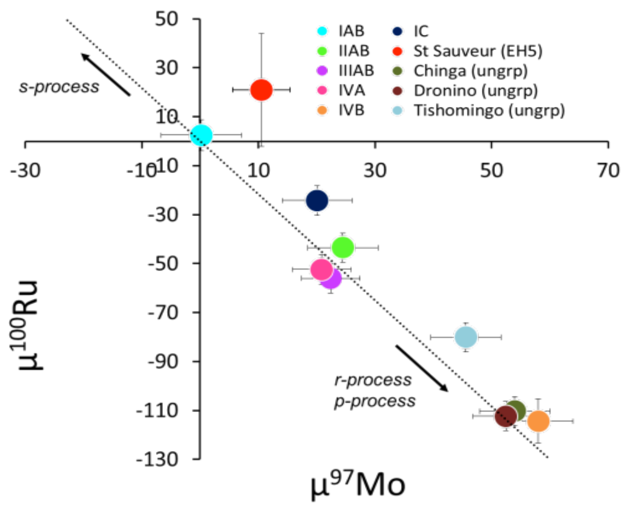


Fig. 2. *The μ^{97}Mo and CRE corrected μ^{100}Ru for meteorite groups and individual meteorites from this study. The bulk silicate Earth (BSE) value for each element is assumed to be 0. Dotted line represents a mixing line between s-process Mo and Ru [Dauphus et al., 2004]. Error bars represent the 2σ SD associated with the measurement campaign, or 2 s.e. internal error associated with a single measurement.*

Mineralogic relics of impactors were detected in samples of the lunar regolith (Fagan et al., in press). That work focused on regolith that was assembled into breccias about 2 billion years ago. The result is fascinating. We identified samples of an asteroid never before seen in our meteorite collection. The material appears to be related to carbonaceous chondrites, but has properties that are unlike any known class. This technique is providing very specific information about the impactor population as it evolved with Solar System age, which will constrain dynamical models of that evolution.

While teasing apart those lunar regolith breccias, we discovered a clast of magnetite (Fig. 3). This is the first direct evidence of the oxidation on the Moon that was hypothesized after the discovery of water on the Moon. That result (Joy et al., 2015) was featured on the cover of Meteoritics and Planetary Science. The oxidation occurred either in the vicinity of a volcanic vent or possibly in the lunar crust during an impact cratering event. The oxidation occurred more than 3.8 billion years ago.

To assist NASA with the exploration of modern water deposits on the Moon, we (a) continued to evaluate the most prominent source of volatiles in the south polar region, (b) contributed to an HEOMD-requested white paper on lunar polar volatiles, and (c) convened a short workshop to investigate the regolith properties in polar permanently shadowed regions where the Resource Prospector will explore for water.

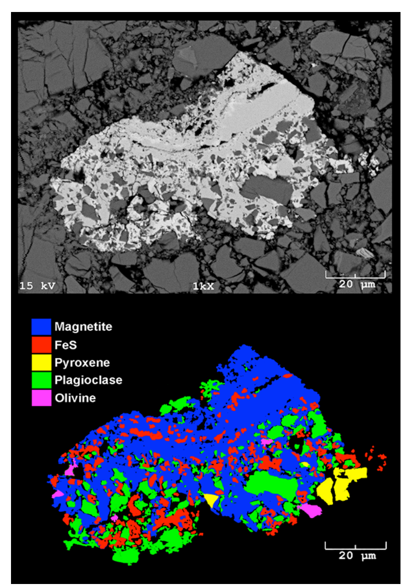


Fig. 3. *Magnetite, an iron oxide mineral, found in lunar regolith sample 60016.*

The integration of science and exploration was also an important theme in studies of the Schrödinger basin on the Moon. Early in Year 2, we published an analysis of a landing site and robotic rover traverse suitable for a human-assisted lunar sample return mission involving astronauts in the Orion crew vehicle (Potts et al., 2015). That is a concept we have been developing as an option for Exploration Mission (EM)-3, EM-5, or EM-6. We were then asked to use that experience to develop landing site and traverse options for a longer-duration version of that concept. The longer-duration mission concept is being developed under the auspices of the International Space Exploration Coordination Group (ISECG) as that group maps out options for The Global Exploration Roadmap (GER). The European Space Agency

(ESA) took the lead on a mission concept study called HERACLES, which was also supported by NASA, CSA, JAXA, DLR, and Roscosmos. In this concept, Orion supports a deep space facility or habitat (DSH) in orbit around the Earth-Moon L2 point. Crew in the facility tele-operate a robotic rover on the surface. A lander with a rover and a reusable ascent vehicle is deployed from the DSH and lands in the Schrödinger basin. The rover collects samples of an important ISRU target – a volcanic pyroclastic vent – and other geological sites of interest, before returning them to the ascent vehicle. The ascent vehicle is launched, rendezvous with the DSH, and crew on Orion return the samples to Earth. The reusable ascent vehicle is refueled and outfitted with a second lander stage and returns to the surface at a second landing site. The rover, with a second set of samples, rendezvous with the second lander and the transfer process is repeated. This mission involves 3 or 4 landings and 3 or 4 sets of samples, with an anticipated sample mass of 10 to 15 kg per ascent. At the beginning of the study, we provided ESA with three notional traverses. Our team's Exploration Science summer interns mapped out the details of two of those traverses, which were delivered to the ESA study team for distribution to all agencies involved. The outcome was presented to the international lunar community, including NASA representatives, at ESA-ESTEC in December 2015.

Our studies involved an assessment of the traverse routes and stations using 0.5 m-resolution LRO-NAC imagery, to assure the feasibility of the traverses. We augmented those studies with additional detailed studies of specific geologic issues. We identified specific boulders within Schrödinger that may contain impact melt produced by the South Pole-Aitken basin-forming impact event (Hurwitz and Kring, 2015), which is a high-priority sample target. With international partners in India and with a SSERVI colleague on the Brown-MIT team, we mapped the locations of faults, boulders associated with those faults, and assessed moonquake activity in the Schrödinger region (Kumar et al., in press). In the HERACLES concept, the second and third landers do not need to carry a rover. Thus, we have extra payload capacity. In one of those landings, a seismic station could be carried to the surface for deployment. Based on two studies by our group, including the new Kumar et al. study, Schrödinger is an ideal location for the deployment of a seismic station. In the other lander, an astronomical radio antenna could be deployed to peer deep into the history of universe.

In addition to those human-assisted lunar sample missions, we have been evaluating near-Earth objects that can be reached by human explorers and providing input for the Asteroid Retrieval Mission. Team members at Arecibo Observatory detected 23 objects (Fig. 4) in its Near-Earth Object Human Space Flight Accessible Targets Study (NHATS), which is a dramatic growth over past years. Rotation rates and the sizes of NHATS detected this year range from ~2 meter 2015 TC25 that rotates once every ~2 minutes to the elongated, multi-kilometer 2003 SD220 that rotates once every ~12 days. Shapes vary from spheroids to the unexpectedly irregular, plus binary and peanut-shaped contact-binary asteroids.

Two of the asteroids were observed in great detail, including 2003 SD220, which was dubbed the Christmas Eve asteroid because of the timing of its flyby of Earth. Radar images revealed an extremely elongated shape over 2.5 kilometers long and a very slow rotation period. Radar observations provided precise astrometry in the form of line-of-sight ranges accurate to less than 1 kilometer while the object was

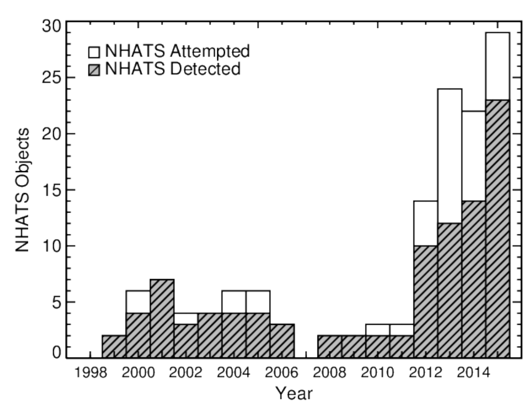


Fig. 4. *Number of detected NHATS objects by Arecibo Observatory. The number of detections has grown substantially with full programmatic support from NASA, including a contribution from CLSE.*

~15 million kilometers from Earth, which is a fractional precision of order 10^7.

In future years, we will be integrating those types of observations with a geologic assessment of surface features and the processes that produced them. In the meantime, we are examining meteoritic samples of near-Earth asteroids to obtain a direct measure of those processes. We have tailored a significant fraction of our work to provide insights into the evolution of carbonaceous chondrite asteroids, as that is the preferred class of materials being targeted by the Asteroid Retrieval Mission. In particular, we are examining brecciated samples of CM and CK materials and, in the spirit of SSERVI, coordinating those studies with two other SSERVI teams. While we are evaluating the petrological properties of the samples, PI Britt of the UCF SSERVI team is providing physical property data and PI Pieters of the Brown-MIT SSERVI team is providing reflectance spectra. Collectively, those analyses will help us better evaluate the geologic processes that occur on CM and CK asteroids.

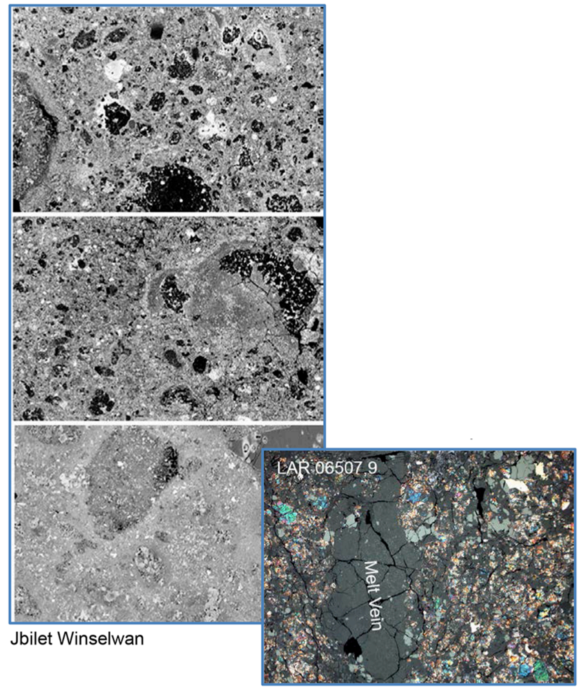


Fig. 5. *Two examples of the meteoritic samples of near-Earth asteroids being studied to evaluate the geologic processes that occur on those asteroids and that may affect the Asteroid Retrieval Mission.*

An important component of our science and exploration activities is training. We involve students and postdocs in every phase of the work described above. We also have a dedicated field training and research program for graduate students. This year we developed a new program in the Zuni-Bandera Volcanic Field of New Mexico. Over the course of a week, students helped map a lava flow so that the process of lava sheet inflation during emplacement can be evaluated. Field mapping was augmented with LiDAR measurements of representative topographic regions. Because the students are often analyzing features on other planets (e.g., the Moon and Mars) using remote sensing techniques, it was essential that we compare and contrast the type of information gleaned from orbit with that available on the surface. For that reason, one of the astronauts that our team had previously trained took a photograph (Fig. 6) from the International Space Station for the students to use.

Co-I Bleacher showing three students features in volcanic basalt (foreground) in the vicinity of a collapsed lava channel (background) that is similar to volcanic rilles on the Moon.

Fig. 6. *Orbital and surface images of the Zuni-Bandera Volcanic Field training and research site.*

2. Inter-team Collaborations

The year began with a workshop that CLSE organized with the SwRI SSERVI team to assess *Early Solar System Bombardment III* (Fig. 7). One of the co-conveners presented a summary of workshop results at the Brown-MIT SSERVI team's microsymposium in March. The co-conveners also published a scientific summary of the workshop for the planetary science community in the Lunar and Planetary Institute Bulletin.

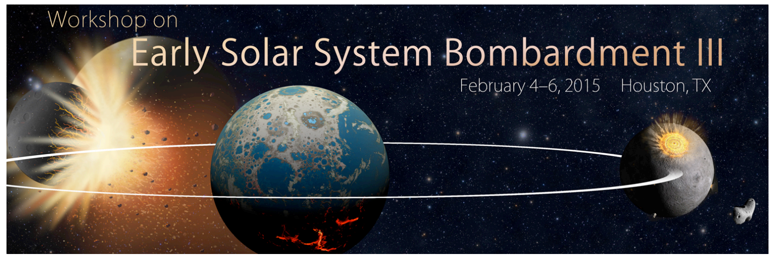


Fig. 7. *Banner of workshop co-convened by two SSERVI teams.*

CLSE organized a multi-SSERVI-team collaborative study of a CM meteorite analogue of some of the possible targets of the Asteroid Retrieval Mission. That work involves the UCF and Brown-MIT SSERVI teams.

CLSE worked with international partners in India and a colleague on the Brown-MIT SSERVI team in a study of faults in Schrödinger basin.

Fig. 8. *SSERVI Director Yvonne Pendleton and PI Phil Bland sign Affiliate Member statement at the Exploration Science Forum.*

CLSE contributed to an HEOMD-requested white paper about lunar polar volatiles, which was an effort led by a co-I of the APL SSERVI team.

A significant amount of CLSE's geochronological study involves our international partners in Australia. In a dramatic expansion of the SSERVI partnership program, NASA and Curtin University signed an affiliate member statement (Fig. 8).

CLSE collaborated with the PI of the Canadian SSERVI affiliate member on the production of a Geological Society of American Special Paper about large impacts and planetary evolution (Fig. 9).

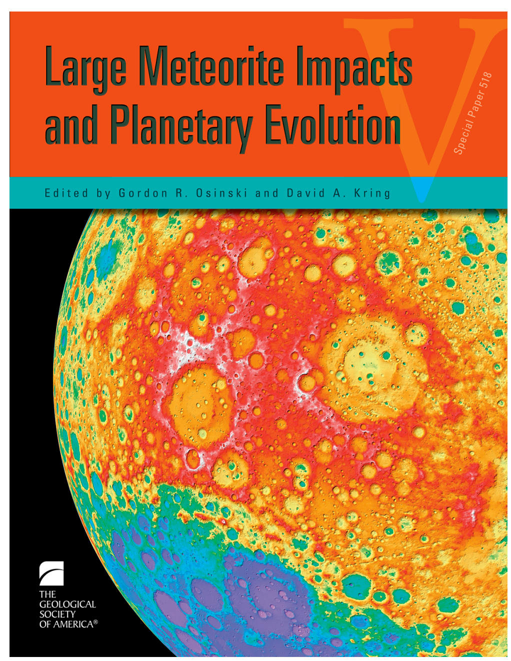


Fig. 9. *Cover of GSA Special Paper.*

In collaboration with the SUNY-led SSERVI team, we proposed and ran a topical session at the 2015 Geological Society of America meeting in Baltimore, MD. The session, T218 Comparative Approaches to Studying Impact Ejecta Deposits and Volcanic Flows, was focused on comparisons between impact and volcanic terrains throughout the Solar System. T218 involved 12 presentations including talks given by participants from three SSERVI teams. GSA also assigned a President's Medal Lecture to this session entitled "Robotic Field Geology" due to the session's focus on science and exploration.

3. Public Engagement (including EPO) Report

2015-2016 Exploration of the Moon and Asteroids by Secondary Students (ExMASS)

- At the 2015 Exploration Science Forum (ESF), the Bellaire High School team placed third in the student poster competition
- 43 students from 10 schools across the country (Fig. 10)
- Student research includes investigations of asteroid Bennu, floor-fractured lunar craters, and physical properties of lunar regolith
- Teams submit research posters to CLSE in April; top four posters selected soon after along with one team to travel to the ESF

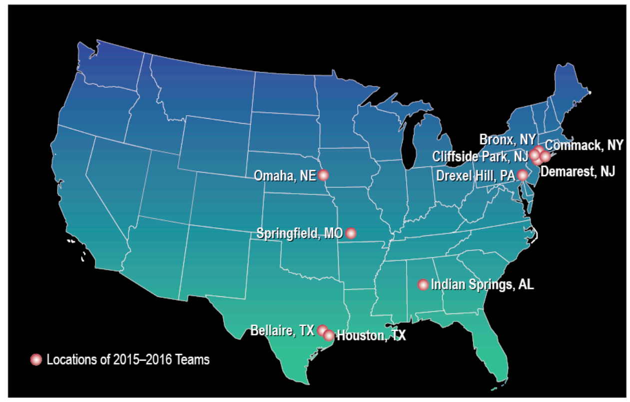


Fig. 10. *Locations of 2015-16 ExMASS schools.*

Traveling Library Exhibits

- Eighth and newest exhibit, *Protecting Our Home*, debuted in 2015
- A final exhibit on meteorites is in preparation for display at LPSC 2016
- 10 unique locations displayed exhibits, reaching an estimated 10,000 people this year

CosmoQuest Google+ Hangouts

- Hangouts featuring SSERVI scientists began in June
- Reach: 60 live viewers, ~400 views of the recordings, estimated 10,000 podcast (audio only) downloads

Public Night Sky Viewing Events

- Continued leveraging LPI's Sky Fest program
- Events included i C Ceres and International Observe the Moon Night (InOMN) celebrations
- CLSE & SSERVI materials distributed at events

Synergies

- Shaner continues to serve as the InOMN Website/social media/listserv manager
- With support from SSERVI Central, Shaner represented InOMN at the 2015 International Public Science Events Conference at MIT
- Shaner assisted with a summer teacher workshop hosted by the IMPACt Team
- Guests for Google Hangouts from CLSE, SSERVI Central, RIS^{4}E, FINESSE, and DREAM2
- Scientists with CLSE, VORTICES, and ISET are student team advisors for the ExMASS program

Arecibo Observatory Space Academy(AOSA)

- A 10-week pre-college research program for students in grades 9 through 12
- CLSE supplemented the existing program, to enhance its reach
- In 2015, AOSA recruited 125 students, 60 during the spring semester, 15 during the summer, and 50 during the fall semester.
- The program as attracted students from nearly every municipality across Puerto Rico and has nearly equal gender participation (45% female).

4. Student/Early Career Participation

New Faculty Team Members

1. Dr. Amy L. Fagan (*Western Carolina University*) – formerly a CLSE graduate student and postdoctoral researcher

Postdoctoral Researchers

2. Dr. Jessica Barnes *(Open University on SSERVI international partner team)* – formerly a CLSE summer exploration intern
3. Dr. Jeremy Bellucci *(Swedish Museum of Natural History)*
4. Dr. Katherine Bermingham *(University of Maryland)*
5. Dr. Patrick Donohue *(University of Notre Dame)*
6. Dr. Debra Hurwitz *(USRA-LPI)* – now at the NASA Goddard Space Flight Institute
7. Dr. Jingao Liu *(University of Maryland)* – now at the University of Alberta
8. Dr. R. E. Merle *(Curtin University)*
9. Dr. Ross Potter *(USRA-LPI)* – now with the SSERVI team at Brown University
10. Dr. Katherine Robinson *(Open University on SSERVI international partner team)* – formerly a CLSE graduate student
11. Dr. Martin Schmieder (*USRA-LPI*)
12. Dr. Barry Shaulis (*USRA-LPI*) – formerly a CLSE graduate student
13. Dr. Joshua Snape *(Swedish Museum of Natural History)* – formerly a CLSE intern in both our summer exploration program and our field training program
14. Dr. Romain Tartèse *(Open University)*

Exploration Science Graduate Student Summer Interns

15. Shelby Bottoms *(University of Colorado, Boulder)*
16. Abigail Calzada-Diaz (*Birkbeck College, University of London*)
17. Mark Leader (*University of Texas, Austin*)
18. Dayl Martin (*University of Manchester*)
19. Francesca McDonald (*University of Manchester*)
20. Sean O'Hara (*University of Illinois at Chicago*)
21. Sarinya Paisarnsombat (*University of New Brunswick*)
22. Edgar Steenstra (*Vrije Universiteit Amsterdam*)
23. Christian Venturino (*University at Buffalo*)

Field Training and Research Program at the Zuni-Bandera Volcanic Field

24. Jessica Ende *(University of Tennessee)*
25. Keenan Golder *(University of Tennessee)*
26. Jane MacAurther *(University of Leicester)*
27. Ryan Nickerson *(Washington University)*
28. Kirby Runyon *(Johns Hopkins University)*
29. Nicole Thomas *(University of New Mexico)*

Graduate Student Researchers

30. David C. Burney *(University of Notre Dame)*
31. Timothy Gregory *(The University of Manchester)*
32. Fiona Thiessen *(Swedish Museum of Natural History)*
33. Emily Worsham *(University of Maryland)*

Undergraduate Student Researchers

34. Adeene Denton *(Rice University)*
35. Stefan Farsang *(University of St. Andrews)*

High School Student Researcher

36. Miriam Matney *(Clear Lake High School)*

Solar System Exploration Research Virtual Institute

Hosted at Brown University

Prof. Carlé M. Pieters, PI

http://www.planetary.brown.edu/html_pages/brown-mit_sservi.htm

SSERVI

Evolution and Environment of Exploration Destinations [SEEED]

Co-Investigators at
MIT
Carnegie
AZ State Univ.
Mt. Holyoke
Univ. Tennessee
College of Charleston

Collaborators from
UC Santa Cruz
APL
Case Western
Consultants

Collaborators from
Russia,
Germany, UK,
Canada, France,
Ukraine, Japan

SSERVI Annual Report: January 2015 – January 2016

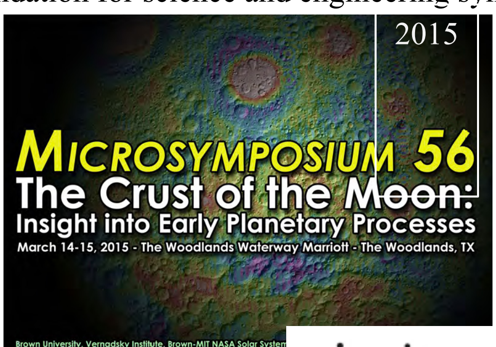
Overview:

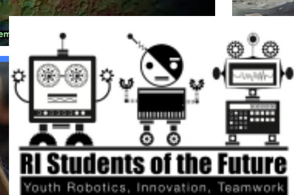
This report covers the second year of SSERVI activities [from January 2015 through January 2016]. Our *SSERVI Evolution and Environment of Exploration Destinations* (SEEED) team is hosted by Brown University with major contributions from Co-Investigators at MIT and five additional institutions. We partner with collaborators from another four institutions as well as seven foreign countries. Altogether, SEEED participants include 24 CoIs and 19 Collaborators. We draw on the strength of ongoing and proposed research activities of a diverse and highly talented team coupled to a philosophy of strong mentoring of young scientists and engineers.

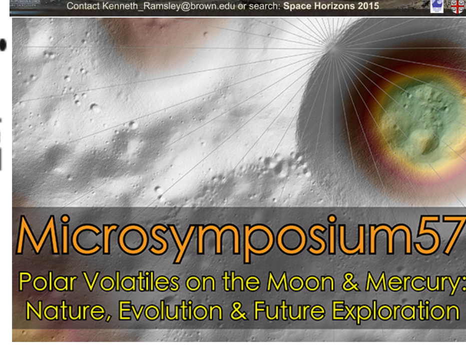
Our principal objective is to create a virtual center of excellence focused on the science and environment of exploration targets. SSERVI targets currently include asteroids, the Moon, and the moons of Mars. Our implementation includes robotic and human exploration synergy and is structured to not only a) *build bridges within the community* and b) *produce the next generation of knowledgeable and qualified planetary scientists and engineers*, but also to c) *attract some of the best minds into the field and keep them involved*.

SEEED Community Involvement and Leadership:

In addition to integrating SSERVI focused activities into the academic and research environment at institutions of our SEEED team (see appendix), we sponsor workshops on cutting-edge topics that involve the broader community. Examples in 2015 include the Microsymposium (March: Houston) and Space Horizons (February: Brown), both of which promote a strong element of discussion and are attended by scientists, astronauts, engineers, students, and NASA officials (programs available on our SEEED website). We actively participate in focused workshops (see appendix). SEEED also sponsors local events that build a foundation for science and engineering synergy (RI Robot Block Party).







RI Robot Block Party April 15, 2015

Near the end of 2015 we crafted Microsymposium 57 “Polar Volatiles on the Moon & Mercury: Nature, Evolution & Future Exploration”. For Micro57 we added posters that are specifically focused on potential landing sites. The diverse program is attached as an appendix.

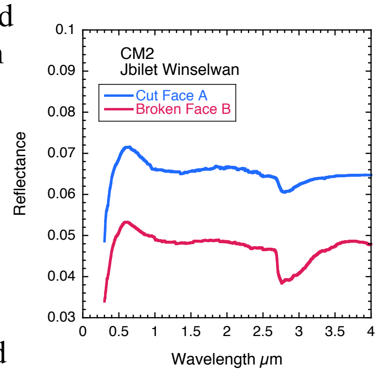
The ***Reflectance Experiment Laboratory*** (RELAB) is serving the community very well by providing high quality spectroscopic data that are fundamentally relevant to NASA science and exploration missions and Research & Analysis programs. See the separate publication list of broad research using RELAB data at: http://www.planetary.brown.edu/relabdocs/relab.htm.

SSERVI Inter-Team Collaboration:

Phobos Virtual Graduate Course: SEEED and CLASS jointly developed and carried out a graduate-level course on Phobos with lectures led by experts in the field supplemented with additional readings. Five SSERVI teams provided several speakers. These weekly lectures were public in real time through Webex and were well-attended. Time after the lecture was reserved to allow question and answers from all participants. The schedule (below) addressed principal issues associated with Phobos (and Deimos). Lecture slides, recorded lectures, and prepared background material can be found through our course website. Several universities arranged formal course credit by structuring additional coordinated activities through the home institution.

Monday	**Topic**	**Speaker**
Sept 14	Introduction [discovery, physical properties, orbit…]	Dan Britt
Sept 21	The Age and Cratering History of Phobos	Nico Schmedemann
Sept 28	The Formation & Effects of Stickney Impact on Phobos	Ken Ramsley
Oct 5	The Character and Origin of Phobos' Grooves	John Murray
Oct 12	Ambiguity of Compositional Data for Phobos and Deimos	A. Rivkin/R. Klima
Oct 19	Geology and Geomorphology of Phobos and Deimos	Sasha Basilevsky
Oct 26	Origin of Phobos: Dynamical Evolution	Joe Burns
Nov 2	Origin of Phobos: Co-accretion, Big Impact & Issues	Robin Canup
Nov 9	Microgravity within the Mars Gravity Well	Dan Scheeres
Nov 16	Properties of Meteorite Analogues	Chris Herd
Nov 23	Space Weathering and Regolith, Dust	C. Pieters/M. Horanyi
Nov 30	Phobos-Deimos ISRU	P. Metzer, R. Mueller
Dec 7	Phobos as an Exploration Destination and a Base for Mars Exploration	Mike Gernhardt
Website	http://www.planetary.brown.edu/planetary/geo287/PhobosDeimos/	

Integrated analyses of CM meteorite Jbilet Winselwan: David Kring and Mike Zolensky of LPI-JSC CLSE initiated a consortium analyses of the primitive (shocked) Jbilet Winselwan meteorite, a possible proxy for the ARM target. SEEED has measured the visible-infrared spectrum of first the chip and then a powder carefully prepared to avoid any alteration near the fusion crust and CLASS is accurately measuring bulk properties (density and porosity). This is a very dark meteorite, but subtle spectral variations are observed, largely with variations of texture.



SSERVI Site Visits: Four highly productive Site Visits enabled SSERVI Teams to explore the research activities and facilities of other SSERVI teams. The host team typically spends 1-1.5 days showcasing ongoing team research and giving local students and young scientists an opportunity to network with the broader community. These inter-team extended opportunities have strengthened our SSERVI integrated approach and revitalized our exploration and research goals.

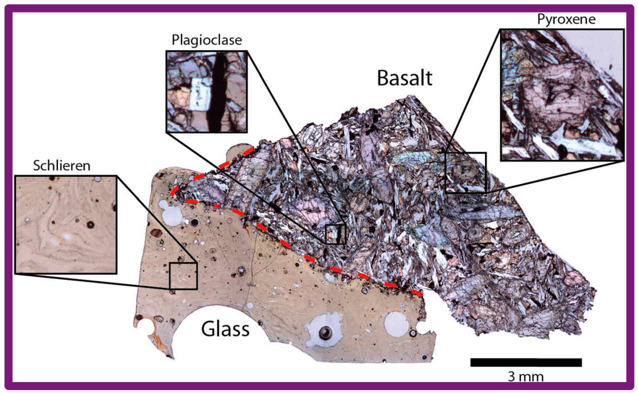
SEEED Science and Exploration Themes:

SEEED research activities encompass four integrated themes with several near- and long-term goals. The active research and academic environment at SEEED institutions along with world-class research facilities enable broad participation. In this context, international involvement is viewed as an integral and long-term investment. This report can highlight only a few examples of the many accomplishments of the SEEED team during the second year of SSERVI. A more complete overview is found in the attached Appendix of Publications from SEEED activities during SSERVI's second year.

I: Thermal/Chemical Evolution of Rocky Bodies

What's new in lunar magnetism?

Jennifer Buz, B. P. Weiss, S. M. Tikoo, D. L. Shuster, J. Gattacceca, and T. L. Grove
JGR-Planets, 2015
Magnetism of a very young lunar glass
Sonia Tikoo, M., J. Gattacceca, N. L. Swanson-Hysell, B. P. Weiss, C. Suavet, C. Cournède, *JGR-Planets*, 2015
Preservation and detectability of shock-induced magnetization

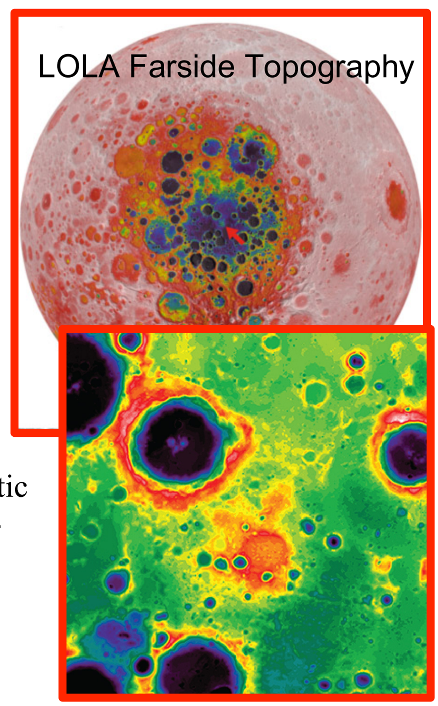


The latest active period of a lunar dynamo is better constrained. No stable NRM is identified in either a young glass (<7 Ma) or the older host basalt (3.35 Ga). Thus, combined with previous work identifying the existence of a core dynamo prior to 3.5 Ga, there is no evidence for a core dynamo at or after 3.35 Ga.

The detectability of shock-induced magnetism is challenging. Shock remanent magnetization (SRM) may persist over geologic timescales, but is relatively easily removed by alternating field methods. SRM is often obscured by other forms of remanence in shocked natural samples.

What's new in the center of the enormous SPA?

D. Moriarty and C. Pieters, *Geophys Res. Let*. 2015
The nature and origin of Mafic Mound in the South Pole-Aitken Basin



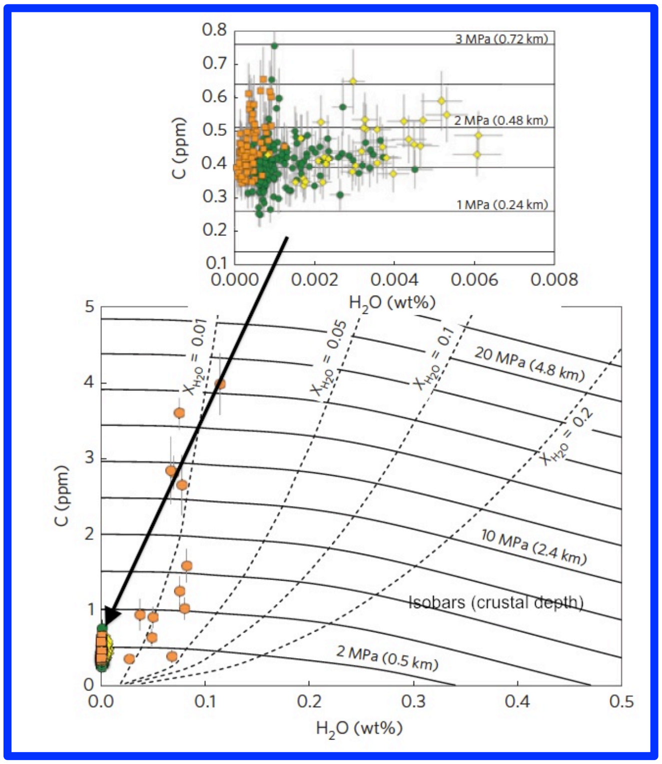
Data from Chandrayaan-1, LRO, and GRAIL have characterized an unusual feature found in the center of the deepest portion of SPA. This "Mafic Mound" is ~75 km in diameter, elevated ~1 km above surrounding terrain, exhibits distinctive mafic composition that contain Fe,Ca-rich pyroxene throughout, and is a small positive gravity anomaly. This Mafic Mound is thought to be a unique magmatic construct related to SPA's formation and evolution. Such non-mare viscous magmatism would represent a newly recognized product of basin-forming impacts on the terrestrial planets.

What's new with lunar water?

D. <u>Wetzel</u>, E. Hauri, A. Saal, M. Rutherford, *Nature GS*, 2015

Carbon content and degassing history of the lunar volcanic glasses

Volcanic glasses observed on the lunar surface have been interpreted as the products of volatile-rich, fire-fountain eruptions. Revised estimates of the water content of primitive lunar magmas have overturned the notion of a volatile-poor Moon, but degassing of water-rich vapour during volcanic eruptions is inconsistent with geochemical and petrological observations. New high-precision measurements of indigenous carbon contents in primitive lunar volcanic glasses and melt inclusions were obtained. These data, in combination with solubility and degassing model calculations, suggest that carbon degassed before water in lunar magmas, and that *the amount of carbon in the lunar lavas was sufficient to trigger fire-fountain eruptions* at the lunar surface. After correcting for bubble formation in the melt inclusions, the primitive carbon contents and hydrogen/carbon ratios of lunar magmas fall within the range found in melts from Earth's depleted upper mantle. These findings are also consistent with measurements of hydrogen, fluorine, sulphur and chlorine contents, as well as carbon and hydrogen isotopes, in primitive lunar magmas. Altogether, *the data strongly suggest a common origin for the volatile elements in the interiors of the Earth and Moon*.

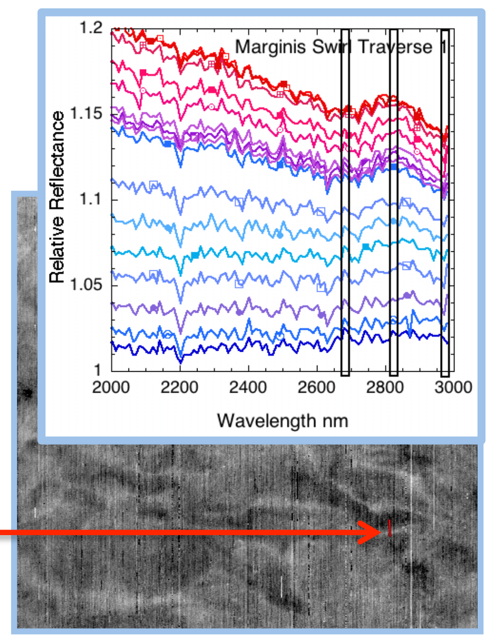


What's new about (no) water at swirls?

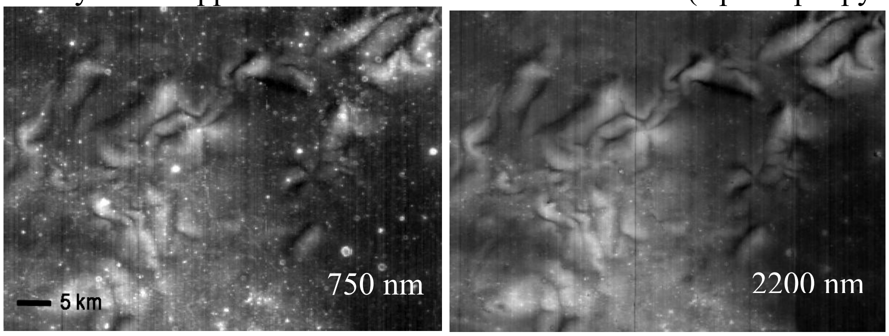
C. Pieters and I. Garrick-Bethell, LPSC46, 2015

Hydration Variations at Lunar Swirls

Small amounts of OH/H2O are detected everywhere across the lunar surface. The leading hypothesis for the origin of this surficial 'water' is formation by solar wind H interacting with the exposed O of lunar silicates. M3 high spatial and spectral resolution *Target* data had definitively shown that the bright swirls exhibit a ~2% weaker OH feature than surrounding soils. The only example of Target data for a swirl (at Marginis) is shown on the right. Variations in strength of the diagnostic OH feature at 2800 nm is mapped (dark is weaker feature) and illustrated by a spectral traverse across the bright swirl.



Incidentally, although the strong local magnetic anomalies at swirls apparently shield the surface from H, M3 data also show that the high albedo areas at swirls is inconsistent with low space weathering: they do not follow the same trend as fresh impact craters, as illustrated in the figures below by the disappearance of fresh craters at 2200 nm (a principal pyroxene absorption).



III: Regolith of Airless Bodies (& Space Weathering)

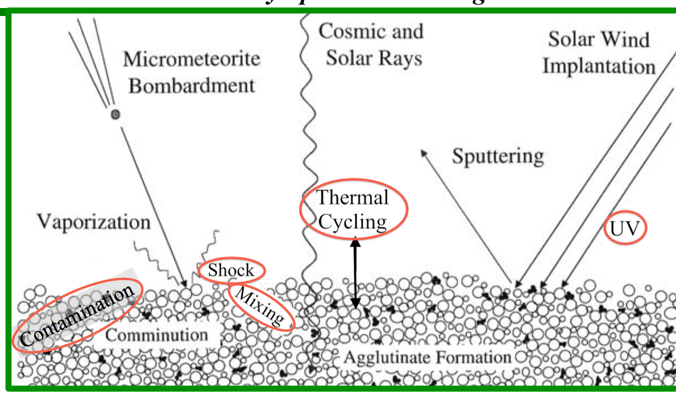
What's new about Space Weathering Processes?

C. Pieters (#2047); K. Donaldson Hanna et al (#2020); L. Taylor (#2032), presentations at *Space Weathering of Airless Bodies*, LPI Houston, November, 2015

The Many Forms of Space Weathering;

Effects of Space Weathering on Thermal Infrared Emissivity Spectra of Bulk Lunar Soils

Lunar Soil Simulants Cannot Reproduce Apollo Lunar Soils With Many Space Weathering Products



Space weathering issues are addressed across several SEEED activities [Jbilet Winselwan consortium, Phobos analyses, swirls, laboratory experiments, etc.). Our understanding of the character and scope of both the processes active in the space environment and the products produced in specific planetary environments have evolved considerably over the last decade. Breakthrough integrated experiments identified nano-phase metallic iron ($npFe^0$) deposits on lunar soil grains as the principal product of lunar space weathering and the cause of optical alteration. This initiated an ongoing discussion of whether the $npFe^0$ was the result of micrometeorite impact vaporization or solar wind sputtering effects. Since then it has been recognized that such 'lunar-like' space weathering is undetectable at different parts of the solar system (Vesta, etc.), and other processes (contamination, mixing, thermal cycling, UV radiation) dominate. These in turn produce different physical and optical effects. Processes marked with red above are now recognized as important for non-lunar environments. *Space weathering is not a single process and each environment/target produces quite different effects.*

IV: Science and Engineering Synergism

All SEEED research activities interweave aspects of both science and engineering. Specific recent additional examples include: **CubeSat:** Students in Brown Engineering formulated a CubeSat Project that won a NASA competition. SEEED Students served as a mentoring and "Standing Review Board" for the project, further enhancing science and engineering mutual understanding and synergism. **Engineering Mission Design Class:** SEEED Students at Brown continued to collaborate (Geosciences and Engineering) on an annual mission design class, exploring various cutting edge technologies and mission architectures to meet science requirements of the future. **Phobos:** As an additional part of the SSERVI Phobos and Deimos Class, Brown students explored mission architecture for determining whether or not Phobos and Deimos were in the critical path for human exploration of the surface of Mars. An LPSC abstract and poster resulted from this class and will be presented by the students at LPSC47 in March. **Design Reference Mission:** We have initiated a SEEED lunar design reference mission to the Orientale Basin of the Moon that includes an international team. This paper was successfully presented at the recent ESA Moon 2020-2030 meeting in the Netherlands [Head et al.]. **Space Horizons:** SEEED co-sponsors this important venue for science and engineering synergism, involving students and faculty. Space Horizons 2015 (https://spacehorizons2015.wordpress.com/) focused on "McMurdo on the Moon" and Space Horizons 2016 (http://www.spacehorizonsworkshop.com/#2016) emphasizes the "International City on the Moon". **Microsymposia** (see above) co-sponsored by SEEED continued to draw scientists, Astronauts and Engineers for fruitful discussions on future science and engineering opportunities.

SEEED Education / Public Engagement (EPE)

Public Engagement initiatives are an important component in all the above activities. In addition, SEEED and our sister SSERVI team, CLASS, have developed an integrated public engagement program that is jointly sponsored by both SSERVI teams. CoI Cass Runyon from the College of Charleston directs our integrated program. Throughout the second year of SSERVI activities, our Education Public Engagement (EPE) team was actively engaged in training pre-service and in-service educators from both formal and informal institutions across the country, working with students and engaging the public on a wide range of SSERVI-related topics.

Our EPE leaders formed a core team of dynamic science educators, authors, artists and storytellers from around the country to help develop engaging inquiry-based, hands-on activities using SSERVI data and resources. This dedicated group of educators remains a core of our ongoing EPE program. They met again in August, 2015 to develop, test and redesign a set of formal lessons using current SSERVI data and imagery. Our EPE team is focusing on three areas using SSERVI content: 1) infusing arts into traditional science, technology, engineering and mathematics (STEM) lessons; 2) integrating formal, informal and out-of-school experiences to foster content retention; and 3) broaden audience reach to include *all* learners, especially those with disabilities. This is a sustained commitment and our EPE Team continues to communicate and work with this core group of educators via Wiggio, an online collaborative tool and meeting site. Divided into teams (science, engineering, technology), the group has been actively testing and adjusting the SSERVI science and technology related curricula and activities in their respective education settings.

As a separate initiative, our EPE Team is working with an undergraduate student and a part-time staff member who are Blind. They are helping to develop, review, and test SSERVI – related curricula and activities vetted by the EPE Core Team. Three tactile guides – graphics and related text – are in final draft. In addition to developing resources for the sight impaired, our EPE Team is also actively working with a teacher who is Deaf and who works with students whose first language is not English. She is assisting with resource development, and is also helping to develop a list of modifications and / or adaptations needed to ensure that we address Universal or Inclusive Design.

One of the many highlights of the year was being able to participate in Camp Happy Days, a camp for children with Cancer. Our EPE Team shared a variety of hands-on activities and talked to the campers about space exploration. One very keen camper (on right) has the dream of working with NASA to explore rocks from other worlds. He was full of questions and eager to hold the Moon (lunar education disk) for as long as he could!

SSERVI Evolution and Environment of Exploration Destinations

SEEED

Annual Report Appendices:

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Exuberant Yuri Gagarin, two SEEED students, two faculty, and a Chinese visitor in Moscow

Local student guides and helpers at IKI 50th Celebration banquet + Russians making a toast

Korean banquet with KASI colleagues and students

YURT Emersion Exploration

SEEED Snapshots 2015

Continuing Education Seminars and Field Trip

SEEED Students and Early Career Participation: 2015

(* indicates cross-team collaboration)

SEEED Students who have been involved with SSERVI activities and/or a lead author on a publication are listed below. Students who graduated in 2015 are indicated as a recent graduate.

Brown, Stephanie	MIT PhD student
Buz, Jennifer	MIT MS student; now graduate student at CalTech
Cannon, Kevin	Brown PhD student
Cassanelli, James	Brown PhD student
Caswell, Tess	Brown PhD student
Caves, Lindsay	University of Tennessee PhD student
Chan, Nicholas	Brown undergraduate student
Deutsch, Ariel	Brown PhD student
Dhingra, Deepak*	recent Brown PhD graduate; now post-doc at University of Idaho
Dygert, Nicholas	recent Brown PhD graduate
Eckley, Scott	University of Tennessee PhD student
Ermakov, Anton	MIT PhD student
Fink, Sam	College of Charlston undergraduate
Fu, Roger	recent MIT PhD graduate; now post-doc at Carnegie
Greenberger, Rebecca	recent Brown PhD graduate; now post-doc at CalTech
Hahn, Timothy	University of Tennessee PhD student
Hoffer, Quincy	College of Charleston undergraduate
Jawin, Erica*	Brown PhD student
Jozwiak, Lauren	Brown PhD student
Li, Shuai	Brown PhD student
Lucas, Michael	University of Tennessee PhD student
Martin, Audrey	University of Tennessee MS student
Mayer, Caitlyn	College of Charlston graduate student
Moriarty III, Daniel*	Brown PhD student
Pack, Natalie	College of Charlston graduate student
Prissel, Tabb	recent Brown PhD graduate
Qiao, Le	visiting graduate student at Brown
Scheinberg, Aaron	recent MIT PhD graduate
Tikoo, Sonia	recent MIT PhD graduate; now post-doc at UC Berkley
Williams, Kelsey	recent Brown undergraduate; now graduate student Washington U.
Williams, Mariah	College of Charlston undergraduate

Postdoctoral Researchers:

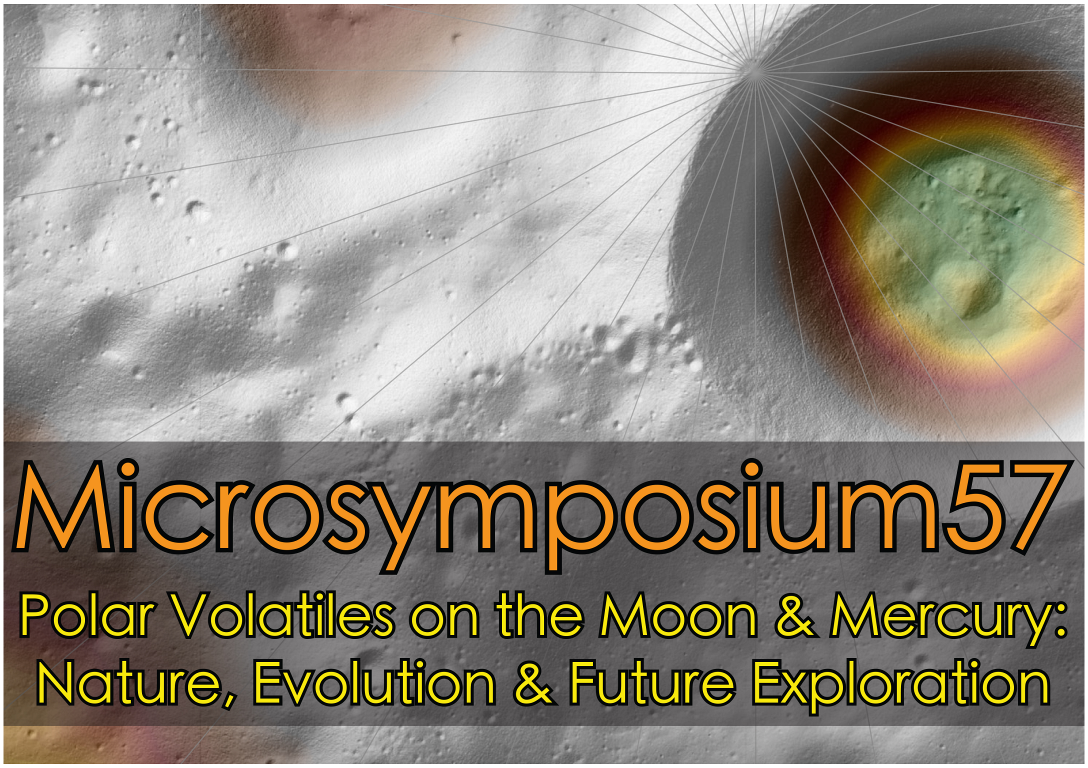
Baker, David M. H.	Brown early 2015; now post-doc at NASA
Bryson, James	MIT
Oran, Rona	MIT
Potter, Ross*	Brown [previously a postdoc at LPI]
Sklute, Eli*	Mount Holyoke
Wiseman, Sandra	Brown
Wetzel, Diane	Currently at Anadarko (oil company); Brown 2014 PhD
Whitten, J. L.	Currently postdoc at Smithsonian; Brown 2014 PhD

New Faculty Hire:

Johnson, Brandon	Assist. Prof. at Brown [recent post-doc at MIT]

2015 Conferences, Workshops and Meetings
Where SEEED participated and several presentations were made

February 2015	*Space Horizons*, Brown University
	Early Solar System Bombardment, LPI, Houston
March 2015	*Brown-Vernadsky Microsymposium 56* Houston
	Lunar and Planetary Science Conference 46
April 2015	*European Geosciences Union*, Vienna, April 2015
July 2015	*SSERVI Exploration Science Forum*, AMES
	Award: Shoemaker Distinguished Lunar Scientist: CM Pieters
October 2015	*Russian Space Research Institute (IKI) 50th Anniversary* (invited talks)
	The Sixth Moscow Solar System Symposium, Moscow
	Korea Astronomy and Space Science Institute [KASI] (invited talk)
	Korean Space Science Society Meeting [KSSS] (invited talk)
November 2015	*Geological Society of America*
	Award: Penrose Medal: JW Head
	Space Weathering of Airless Bodies, LPI Houston
December 2015	*American Geophysical Union*, San Francisco (student talk invited)
	Outstanding Student Paper Award: L. Jozwiak
	International Symposium on Moon 2020-2030, ESA
	Students for the Exploration and Development of Space (SEDS), ESA



The Woodlands Waterway Marriott, Montgomery Ballroom, The Woodlands, Texas
March 19-20, 2016
http://www.planetary.brown.edu/html_pages/micro57.htm

Micro 57: Polar Volatiles on the Moon and Mercury

The discovery of polar volatile materials on the Moon and Mercury has revolutionized our thinking about the origin, evolution and exploration of these significant scientific legacies and potential future resources. What is the nature and distribution of these materials? How did they form? What is their age? How are they maintained? What is their abundance? What records do they hold of the geological, geochemical and orbital history of the Moon and Mercury? What can they tell us about the degassing history of the Moon and Mercury? What can they tell us about the flux of comets in the Solar System? What can we learn from the comparison of polar volatile materials on Mercury and the Moon? How do we explore these materials in the future to address these questions and to assess their potential for supporting human exploration? In this Microsymposium, we will explore our current knowledge of these materials and seek to identify the key questions, goals and objectives in order to underpin and motivate future exploration. We will review current exploration plans, including the U.S. Resource Prospector, Russian Luna and ESA BepiColombo missions.

Saturday, March 19, 2016 (1 PM-6:30 PM)

1:00 PM: Introduction: ***Jim Head, Carle Pieters and Maria Zuber***

1:10 PM: **The Nature of Polar Volatile Materials on Mercury and the Moon**

Ariel Deutsch: Mercury's Polar Deposits as Revealed by MESSENGER Mission Image Data: Correlation of Radar Bright Deposits and Large PSRs.

Nancy Chabot: Mercury's Polar Deposits as Revealed by MESSENGER Mission Image Data: Surfaces of Polar PSR Regions Revealed by WAC Images.

Paul Lucey: Albedo of Lunar Polar Regions at 1064 nm and Implications for Volatiles.

Amanda Hendrix: Far-UV Albedo: Diurnal Variations in Hydration and a Probe for the Lunar Cryosphere.

Dana Hurley: Volatile Sources, Mobility and Diversity on the Moon.

Paul Hayne: New and Evolving Views of the Moon's Volatiles and Implications for Mercury.

Kathleen E. Mandt: LRO-LAMP Detection of Geologically Young Craters within Lunar Permanently Shaded Regions.

David Lawrence: Synthesis: Remote Sensing Evidence for Polar Volatiles on the Moon and Mercury.

3:50 PM: **The Origin and Long-Term Stability of Polar Volatile Deposits**

Matt Siegler: True Polar Wander and Spin-axis/Orbital Parameter Variations of the Moon and Mercury and the History of Permanently Shadowed Regions.

Bill Bottke: External Volatiles: Comets at the Moon and Mercury.

Parvathy Prem: Transport of Water in a Transient Impact-generated Lunar Atmosphere.

Alberto Saal: Internally Derived Lunar Volatiles: A Synthesis.

Steve Parman: Internally Derived Mercury Volatiles: A Synthesis.

Ralph Milliken: Lunar Equatorial Surface Volatiles: Lunar Pyroclastics.

Nathan Schwadron: Time-of-Day Dependence of Albedo Proton Flux in the Near Surface Hydration Layer?

6:20 PM: ***Myriam Lemelin***: **Introduction to Candidate Polar Landing Sites Poster Session**

6:30 PM: Special Poster Session and Reception

Candidate Polar Landing Sites Posters

- ***Myriam Lemelin***: High Priority Landing Sites for in situ and Sample Return of Polar Volatiles.
- ***Jessica Flahaut***: Science-rich Landing Sites: Lunar Volatile Exploration.
- ***Makiko Ohtake***: JAXA Lunar Polar Exploration Regions of Interest. (I)
- ***Mikhail Ivanov***: Russian Luna Polar Landing Site Analyses.
- ***Rick Elphic***: Resource Prospector Landing Site Considerations: From Measurement Priorities to Mission Constraints.

Polar Volatiles on the Moon and Mercury Posters

- ***Svetlana Pugacheva***: Ice Distribution in Lunar Polar Soils: A Synthesis. (I)
- ***Erwan Mazarico***: Mercury's North Pole Illumination-modeling Simulations.
- ***Greg Neumann***: Mercury Laser Altimeter 1064 nm Reflectance in the North Polar Region.
- ***Ted Raab***: Halogens: Constraints from Meteorites, Apollo/Luna Measurements and Theoretical Geochemistry. (I)
- ***Stuart Robbins***: Distribution of Lunar Polar Craters and Correlations with LRO-LAMP Lyman-alpha Data.
- ***Ted Roush***: Imaging and Near-infrared Spectral Monitoring of Volatiles while Drilling into Frozen Lunar Simulant.
- ***Sruthi Uppalapati***: Tycho: New Analyses of its Age, Ejecta Distribution, and Effects on the Surface of the Moon.
- ***Stephen Wood***: Thermal Modeling of Regolith Properties in Super-cold Permanently Shadowed Regions (PSR) on the Moon and Mercury.
- ***Wenzhe Fa***: Mini-RF PSR Data: Detection of Ice or Rocks?
- ***Martin Slade***: New Earth-based Radar Observations of the Lunar Poles to Characterize Ice Abundance and Inclusions.
- ***Jim Fastook***: Polar Glaciers on Mercury?
- ***Wes Patterson***: Mini-RF/AO Bistatic Observations of the Floor of Cabeus Crater and their Implications for the Presence of Water Ice.

Sunday, March 20, 2016 (8:30 AM-12 Noon)

8:30 AM: **The Origin and Long-Term Stability of Polar Volatile Deposits**

Darby Dyar: Externally Derived Lunar Volatiles: Solar Wind.

David Paige: Outstanding Questions Regarding Polar Volatiles on the Moon and Mercury.

9:10 AM: **Future Exploration Plans for Polar Volatile Deposits**

Barbara Cohen: Lunar Flashlight 6U CubeSat Mission.

Pam Clark: Lunar Ice Cube 6U CubeSat Mission.

James Carpenter: ESA Plans for Lunar Polar Exploration. (I)

Maxim Litvak: Luna Missions to the Polar Regions of the Moon.

David Rothery: The BepiColombo Mission to Mercury.

Tony Colaprete: Resource Prospector: Overview and Current Status.

Jen Heldmann: Resource Prospector: Science Goals & Implementation.

11:30 AM-12 Noon: Discussion and Conclusions: ***Jim Head, Carle Pieters and Maria Zuber***

12:00 Noon: Adjourn

VORTICES Report: Year 2

1. *Team Project Report*

The VORTICES team has made significant progress in Year 2 of funding. We focus here on several key research results and highlights for the scientific themes being explored by the VORTICES team. Though organized below and in the proposal by theme, the projects being investigated by our Co-I's often address multiple topics, all basically encompassed by the broad scientific goal of understanding the nature of the uppermost surface of asteroids, the Moon, and other airless bodies and how heat and volatiles interact with it.

The VORTICES team had a highly productive in-person meeting this fall, attended by ~20 participants from as far away as Alaska, Hawaii, Georgia and Arizona. Our team includes experts in many remote sensing techniques, each of which probe different depths of a regolith (Fig. 1), and in our discussions it became clear that there has never been a focused attempt to integrate all of the constraints placed by each of these techniques to provide a cohesive profile of what we understand of the Moon, asteroids or other regoliths. As a result of our discussions at this meeting, we are hoping to convene a Keck-style SSERVI workshop entitled 'Microns to Meters'. The workshop would involve two ~3 day sessions, separated by several months, and ~25 participants who would: 1) focus on understanding the sources, transport, sequestration and destruction of volatiles in the lunar and asteroidal environment as it relates to regolith processes operating on scale of micrometers to meters over different time scales. How do these processes differ between the Moon, NEA and main-belt asteroids (MBA)?; and, 2) focus on understanding the physical properties of lunar and asteroidal regoliths and the processes that produce small particles that form them and how they evolve. Though these topics are already being explored in detail by the VORTICES team, this workshop would engage others in SSERVI and ultimately result in a white paper or other published record that would centralize our understanding both for scientists and HEOMD.

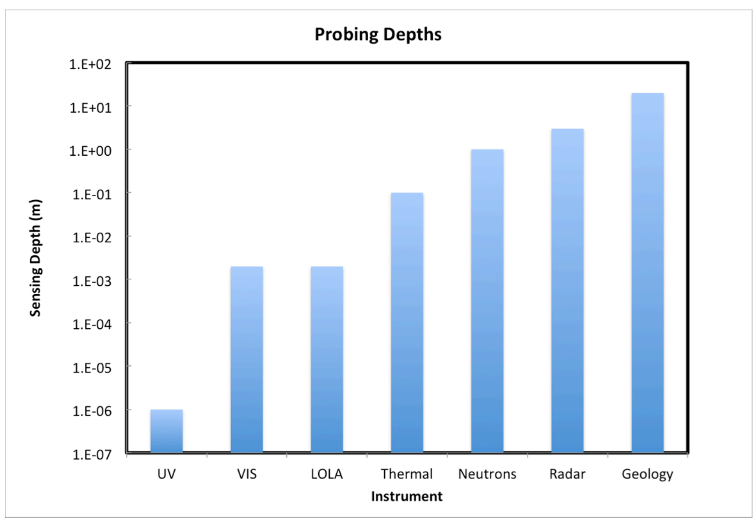


Fig. 1. Range of depths to which different remote sensing techniques are sensitive. By integrating the constraints on volatile content or regolith structure placed by observations from each technique, we can characterize the nature of the upper regolith on the Moon and asteroids.

Theme 1: Volatiles in the Solar System: Sources, Processes, Sinks

The VORTICES team has been investigating volatiles on bodies in the inner solar system through a combination of numerical modeling, laboratory experiments, and spacecraft and telescopic data analysis. On the modeling side, Co-I Hayne has completed improvements to JPL planetary thermal model using constraints from Diviner, including development of a standard set of physical parameters based on discussions within the Diviner team. He has also developed models for estimating asteroid volatile outgassing rates and detectability. Co-I Hurley worked with David Kring to provide inputs for Schrödinger vent paper simulating distribution of OH released from the vent to calculate the delivery efficiency of OH to cold traps. This work has been submitted to Nature Geoscience. Co-I Kulchitsky has continued work on solar wind implantation rate into regolith. This work was presented at LPSC in 2015 and is being prepared for submission and peer-review. Co-I Hibbitts has been working with Lori Feaga on Rosetta cometary modeling and also with the Georgia Tech group to prepare a paper on solar wind production of OH and its grain-scale evolution in the illuminated surface. Co-I Zimmerman has been working to understand how lunar OH and H_2O migrate under realistic heating conditions. He has updated his model to incorporate shadowing of direct sunlight and irregular cell sizes. The model includes new illumination models to be easily added (e.g. include Earthshine, etc.), temperature-dependent thermal conductivity, OH/H_2O diffusion/desorption and incorporation of plasma physics-driven solar wind H source.

In the laboratory, Co-I Hibbitts continues to take UV and IR spectra of lunar and asteroid samples and analogs under ultra-high vacuum, exploring the thermal stability and spectral nature of water and OH. Co-I Hibbitts has measured adsorbed OH and H_2O on anorthite and lunar samples at APL, using a reflectance set up that spans from 150-5500 nm (Fig. 2). One goal is to understand how the 3 micron band can best be interpreted as diagnostic of mineral/rock composition.

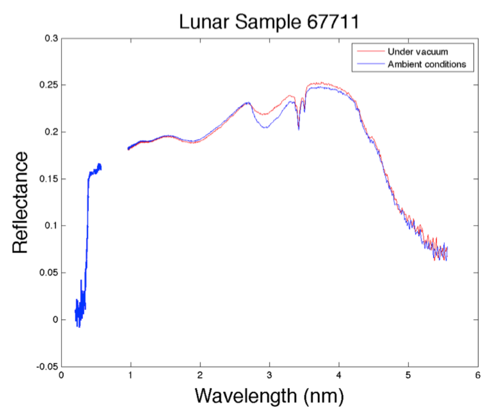


Fig. 2. UV-midwave IR spectrum of Apollo 16 sample under vacuum and ambient conditions.

In addition, Co-I Orlando (at Georgia Tech) and Hibbitts have measured the binding energies and thermal desorption activation energies of water from two lunar mare and two lunar highland samples. The results indicate much stronger uptake and binding of water on the highlands samples, and are being prepared for publication. They are also working on a model explaining temperature and latitudinal dependence of OH on the Moon.

With the assistance of a summer undergraduate intern, Co-I Klima is approaching the characterization of water/OH from another direction, by measuring the internal bound OH in a suite of meteorite and analog lunar samples from the Stillwater intrusion by using transmission microspectroscopy and modeling the absorption bands. This work was presented at DPS and AGU (by B. Young), and is being prepared for publication in early 2016. These samples will then be measured in the vacuum chamber to explore the spectral character of adsorbed OH and H_2O on these samples, to investigate whether internal water can be distinguished from adsorbed water on nominally anhydrous minerals.

Analysis of spacecraft and telescopic data by many VORTICES team members continues, including involvement on LRO-LAMP, Diviner, Mini-RF, and LROC. Much of this work has been highlighted in a lunar volatiles special issue in Icarus, spearheaded by Co-I Hurley. Co-I Cahill has also been officially made a Participating Scientist on LRO-LAMP and is collaborating with the team to investigate aspects of space weathering and volatiles in non-polar and polar regions.

Theme 2: Regolith: Origin and Evolution on Airless Bodies

Regolith evolution is also being explored through a combination of experimentation, modeling, and validation of models using spacecraft data. Co-I Plescia is working to comparing effects of impact and thermal fatigue on the disintegration of rocks to form regolith, performing experiments on mm-scale samples (Fig. 3). To explore this, he and his team are comparing the size-frequency distribution of fragments to the models and experiments of thermal and mechanical fracture. Small-scale (micro) fracturing is controlled by grain size, pre-existing fractures and inclusions (e.g., chondrules). These results are compared to the grain sizes of lunar regolith by compiling data from Surveyor, Apollo, Lunar Orbiter, and LRO for complete particle size-frequency distribution (Fig. 4).

Co-I Greenhagen and Collaborator Bowles have been conducting laboratory experiments in simulated airless body environment investigating the effects of short-duration thermal pulses on fine-particulate surface mid-infrared.

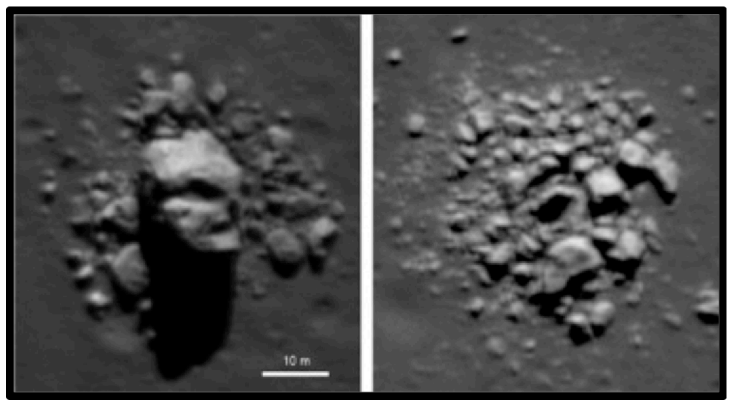


Fig. 3. LROC image shows two boulders ~20 m in diameter. The boulders rolled down a slope to their present position. The question is whether the boulders shattered due to the rolling, to impact processes, to thermal fatigue or some combination of all of these.

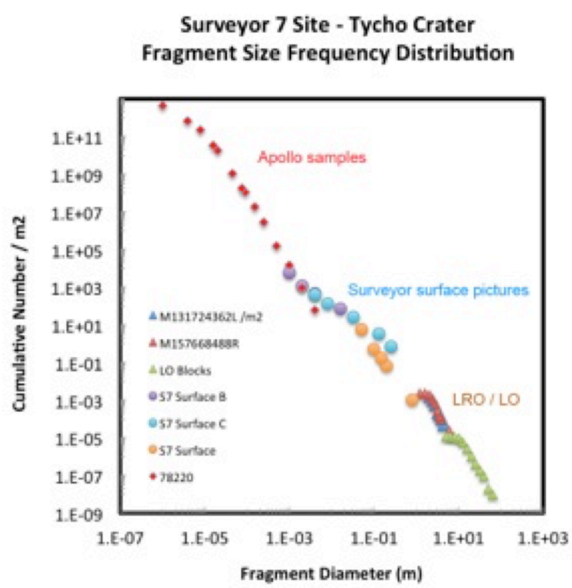


Fig. 4. Observed size-frequency distribution of the regolith from boulders to micron-size particles.

This work will lead to a better understanding of the thermophysical properties of the top mm with implications to remote sensing and thermal modeling of SSERVI bodies. Co-I Siegler has been working on measuring low-temperature thermal conductivity of lunar regolith samples to better understand thermal properties of very cold lunar soil.

A recently accepted Nature manuscript shows that the hydrogen concentrations at the lunar poles are consistent with true lunar polar wander of several degrees. This work identifies a possible paleopole and shows a connection to the formation and evolution of the Procellarum KREEP Terrane. This work included several VORTICES Co-Is; Siegler posed the fundamental true polar wander question and provided the near-surface thermal and ice stability models from models developed by Paige. Miller developed and performed the analyses of neutron datasets, including hydrogen abundance and spatial distribution determinations, as well as the multi-dataset correlation, statistical, and admixture analyses. Lawrence contributed additional expertise related to the interpretation of thermal and orbital geochemistry science.

Co-I Gillis-Davis conducted laser space weathered a mixture of a range of materials, including cronstedtite (~75%) and siderite (~25%), finding large, micron-sized grains stuck onto the grains with melt. These large dark and spectrally neutral particles may explain why some asteroids and perhaps areas on Mercury become spectrally bluer with exposure to space weather. Currently studying the bonding C, N, and H using Valance Electron Energy Loss spectroscopy. He has also explored the effects of submicroscopic Carbon, presenting this work at the Space Weathering meeting in Houston Nov 1-3. The carbon deposits produced spectral effects consistent with VIS/NIR data of low-reflectance materials on Mercury as measured in MESSENGER MDIS and MASCS data.

<u>Theme 3: Resources: Identification and Exploitation and Theme 4: Closing Strategic Knowledge Gaps</u>

In addition to exploring fundamental science question, the VORTICES team works closely with HEOMD to provide input for exploration of the inner solar system. Co-I Stickle has continued working on the polar lighting model for the Moon to identify regions of permanent shadow and light, providing detailed analysis of points at the South Pole of the Moon that may be of interest for human or robotic exploration. PI Rivkin worked with Sam Lawrence on Small Body Environment section of SBAG exploration/SKG white paper and is beginning work on the Phobos SSERVI/(AG) SKG update with members of MEPAG under Bussey's direction. Rivkin is also advising members of FAST team for HEOMD. Finally, Rivkin contributed to the Human Exploration and Science sections of the SBAG Goals Document.

2. *Inter-Team Collaborations (up to 1 page)*

- Rivkin participated in the Britt/Pieters Phobos class.
- Matiella Novak participated in the FINESSE 2015 field expedition to Craters of the Moon (COTM), Idaho as a partnership activity, leading a data collection effort to analyze mushroom cap features present within lave flows at the Kings Bowl site within COTM. She is now analyzing this data from Kings Bowl as well as conducting reconnaissance of similar features within LROC NAC data at impact melt sites on the Moon.
- Co-I Hurley has been working with David Kring on finalizing inputs for Schrödinger vent paper simulating distribution of OH released from the vent to calculate the delivery efficiency of OH to cold traps
- Co-I Hurley guest editor for Icarus special issue on lunar volatiles, also conducts regular "Friends of Lunar Volatiles" team telecons. Both items involve several members of multiple SSERVI teams.

3. Public Engagement and EPO Report

Second year Public Engagement and Education included successful partnerships for International Observe the Moon Night, partnering with other SSERVI teams for formal educator professional development, and participating in student and public engagement events, including those associated with the New Horizons close encounter activities.

The VORTICES team supported International Observe the Moon Night with an event coinciding with the Maryland Science Center's Stargazer Fridays on September 18 in Baltimore, MD. Ninety-three participants engaged in lunar science hands-on activities, lunar and Saturn telescope observations and discussions with VORTICES scientists. Student engagement included participating in a Girl Power event at JHU/APL in March of 2015, with over 800 girls and their families in attendance. Also, the VORITICES Team visited a local Maryland STEM magnet middle school with the Magic Planet. Magic Planet is a spherical display that is very popular and has proven effective in student engagement. It has been especially useful in displaying global data and generating discussions on comparative

planetology as they are taken through an interactive tour of the Solar System. Over 200 6th grade students attended multiple presentations throughout the day on Solar System Exploration science. For an exciting event, the VORTICES team partnered with the New Horizons EPO team during the Pluto close encounter activities of July 2015. VORTICES team members gave presentations on lunar and small body science, as well as NASA Solar System Exploration efforts. For another SSERVI partnering activity, a VORTICES scientist involved with the OSIRIS-Rex mission participated in the SSERVI DREAM2 Explore Workshop and gave a presentation on asteroid science to the educators present at the workshop. A representative from VORTICES also participated in the FINESSE Craters of the Moon field campaign, assisting with mentoring undergraduate students and the Spaceward Bound professional development workshop for educators. Finally, in our second year our website, www.vortices.jhuapl.edu, went live. This website summarizes the VORTICES Scientific Themes and includes biographies of our team members. There are also links to our previous NLSI efforts and research results. Goals for 2016 include continuing partnerships for hosting InOMN events and facilitating a workshop for pre-service teachers, targeting education students at Maryland Historically Black Colleges and Universities. Additionally, VORTICES scientists have volunteered to partner with the FINESSE team to give presentations to the Museum Alliance and NASA Solar System Ambassadors.

4. Student/Early Career Participation

1. Graduated Ms. Grace Green with B. S. in physics from University of Alabama Huntsville, supported by VORTICES, working with Co-I Miller
2. Angela Stickle, postdoc for VORTICES at APL, worked on lighting modeling at the lunar poles and analysis of radar data.
3. Brianna Young, undergraduate from Western Oregon University, worked over the summer at APL preparing samples and measuring their composition and internal water content.
4. Michelle Castro, high school intern at APL, conducted research with LRO data to look at craters ejecta.
5. Tsion Haile, Paint Branch High School, Montgomery County, MD. Worked at APL doing sample preparation and FTIR data acquisition.
6. Ben Wing, Montgomery County Magnet High School, MD. Has worked at APL for the past year doing sample preparation and FTIR, and UV data acquisition. He is pursuing a degree in physics/astronomy at college, in part, because of his experience at APL.
7. Dr Kavan Hazeli, postdoc, Johns Hopkins University, does experiments examining the thermal fatigue of meteorites.
8. Charles El Mir, graduate student, Johns Hopkins University, builds computational models for regolith evolution due to thermal fragmentation on asteroids.
9. Erez Krimsky, undergraduate, Johns Hopkins University, characterizes flaw distributions in rocks and ceramics.
10. Catherine Elder, postdoc, working with Paul Hayne on lunar thermal models.

Co-I Jeff Gillis-Davis supported several students and early-career scientists with his VORTICES-funded laboratory work:

11. Amber Mokelke, undergraduate (2 semesters)
12. Logan Magad-Weiss, undergraduate (1 semester)
13. Parker Crandell, graduate student (2 semesters)
14. Andrew Turner, graduate student (1 semester)
15. Heather Kaluna, graduate student (conference travel)
16. Patrick Gasda, post-doctoral researcher